Applied Research Laboratory

Technical Report

**High Strength P/M Gears for Vehicle Transmissions – Phase II**

by

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# High Strength P/M Gears for Vehicle Transmissions-Phase II

## Phase II-Final Report

by
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This effort accomplished three major objectives. A production capable powder metal (P/M) gear ausform finishing machine was designed by a select machine tool builder (Kinefac Corporation of Worcester, CT). The integration of this machine on the production floor of a powder metal parts manufacturer (Keystone Powder Metal Company, St. Marys, PA), which included the automatic load/unload mechanism and other sub-systems, was defined. The final objective accomplished was the optimization of the ausform finishing process and the total P/M gear manufacturing process to achieve higher gear quality and lower cost, with the use of lower density P/M parts.

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## Executive Summary

The primary objective of this three phased project is to establish powder metal (P/M) steel gears as the preferred component of choice in ground vehicle transmissions. It is well established due to the nature of the process that complex steel parts can be made more economically from P/M, especially in large production volumes. Ground vehicle transmission gears are an ideal candidate for utilizing this benefit with significant economic benefits to the military and the commercial sectors. However, penetration of P/M in power transmission components for ground vehicles has been limited to "lightly stressed" applications only, due to the strength and durability limitations of P/M.

In Phase I of this project it was demonstrated that gears made from P/M and finished by the process of ausform finishing, a thermo-mechanical process developed at Penn State, performed as good, or better, than wrought steel gears manufactured by conventional gear manufacturing processes. It was also established in Phase I that gears could be made more economically utilizing P/M. Following the successful conclusion of the Phase I effort, Phase II was pursued with the following objectives and tasks:

<u>Task 1: Establish design of ausform gear finishing machine for P/M gears:</u> The "Focus" part identified in phase I (New Process Planet gear P/N 17864, component for the transfer case of the HMMWV) was utilized as a basis of this task. Based on this component and with the capability of processing a range of similar components, a concept design sub task was first implemented. This sub task evaluates various machine concepts to establish a production capable ausform gear finishing machine at minimum cost and time. Based on the selected concept and after a Concept Design Review, a complete design package was developed to a point that a machine tool builder could proceed with the actual fabrication of the machine. Costs for fabricating the machine tool was also established by having machine tool builders provide "to build" quotations on the design package.

<u>Task 2: Evaluate integration of ausform finishing machine into P/M gear production line:</u> A design package describing part handling and floor layouts to integrate the ausform finishing machine, defined in task 1, into a P/M pilot facility and into a P/M production facility was developed. This pilot "low volume" production facility is intended to manufacture several P/M vehicle transmission gears for other military contractors and commercial vehicle manufacturers.

<u>Task 3: Optimize process for P/M gears:</u> The efforts in this task were directed to obtaining higher tooth form accuracy on the Standard test (spur) gears, by optimizing the die tooth form. In phase I an acceptable tooth profile had been obtained on the "drive" side of the Standard test gear, which was the side that was tested for strength and durability. The coast side tooth profile was not acceptable and further modifications of the die tooth profile were required to bring this feature to an acceptable level of quality. Acceptable level of quality was prescribed as in the range of A6-A7 as per ANSI/AGMA 2015-1-A01. Gear tooth lead accuracy on the Standard test gear was always acceptable and no effort was expended in this phase on this tooth feature.

Further, development of process parameters and die modifications to satisfactorily process the "focus" (helical) gear, were also investigated. Since a small helical gear had never been processed on Penn State's double-die, ausform finishing machine a significant aspect of the effort was expended in developing satisfactory work holding tooling for this part and establishing the relationships between the machine settings and the lead of the helical gear. Within the time and resources allocated for this phase, significant progress on obtaining the desired profile and lead was accomplished. Additional effort to obtain the desired lead and profile will be considered in the next phase of the effort.

This report summarizes the activities conducted in this phase.

# Abstract

This effort accomplished three major objectives. A production capable powder metal (P/M) gear ausform finishing machine was designed by a select machine tool builder (Kinefac Corporation of Worcester, CT). The integration of this machine on the production floor of a powder metal parts manufacturer (Keystone Powder Metal Company, St. Marys, PA), which included the automatic load/unload mechanism and other sub-systems, was defined. The final objective accomplished was the optimization of the ausform finishing process and the total P/M gear manufacturing process to achieve higher gear quality and lower cost, with the use of lower density P/M parts.

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## Acknowledgement

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# High Strength P/M Gears for Vehicle Transmissions-Phase II

## 1. Introduction

It is a well established fact that complex shaped steel parts, that are required in very high production volumes, can be more economically made with powder metal (P/M). This is primarily because the P/M processing results in net shape with no scrap material and subsequent waste. Other reasons for lower costs are due to the fact that while initial costs for the tooling is high, these costs amortized over large production volumes are very low in comparison to tooling costs in conventional processing. This coupled with very high production rates, that are typical fro P/M processing, also results in lowered part piece costs.

Transmission gears, utilized in military and commercial ground vehicles, have all the characteristics that would make them more economical to manufacture by P/M processes. They are complex in shape and are manufactured in very large volumes (40,000 pieces per day, in one transmission plant is common). However, the surface durability of gears made from P/M, especially as it relates to wear and pitting failure has been insufficient to allow it to replace conventionally manufactured wrought steel gears. In phase I of this project it was demonstrated that P/M gears strengthened by the ausform finishing process out performed conventionally processed wrought steel gears in surface durability and scoring resistance while matching bending fatigue and impact characteristics. Further, the economic benefits of manufacturing gears with P/M were also established in Phase I.

Based on the successful completion of Phase I, Phase II was initiated with the following specific tasks.

## 2. Task 1: Establish Design of Ausform Finishing Machine for P/M Gears

This task was conducted in three separate sub tasks. Task 2.1 was designed to establish several machine concept designs from several machine tool manufacturers. The conclusion of this sub task was the down selection of the machine tool manufacturer who would undertake the preliminary and detail design sub tasks (2.2 and 2.3).

<u>2.1 Concept Design</u>

A "Production Gear Ausform Finishing Machine-Preliminary Requirements" was defined. This document, which defines the ausform finishing process and the basic requirements of the machine tool to conduct this process, is attached in Appendix A. Four machine tool manufacturers (Gleason Corporation of Rochester, NY, Kinefac Corporation of Worcester, MA, Normac of Arden, NC and Escofier (Great Lakes Machinery) of Canton, MI) were contacted to solicit their interest in designing this machine. These builders were contacted on the basis that they were already in the gear manufacturing business in various ways. Only two builders, Kinefac and Normac expressed interest in this effort and they were supplied with Preliminary Requirements document for a preliminary design of the potential machine.

## 2.2 Preliminary Design

Both Normac and Kinefac submitted a preliminary design concepts and presented their individual packages to a combined evaluation panel consisting of individuals from Applied Research Laboratory/The Pennsylvania State University (ARL) and Keystone Powder Metal Co.(KPM), the selected sub-contractor on this phase. After these presentations, conducted on two days, the concepts were jointly evaluated for technical feasibility and costs. Background, prior experience and technical capabilities of the individual companies were also considered. The Kinefac Corporation package was considered the superior concept and based on Kinefac's experience in rolling, was selected as the builder who would be contracted to conduct the detail design of this machine. The concepts presented by the two competing builders and the evaluation leading to the selection of the builder to conduct the detail design is described in the Preliminary Design Report and attached in Appendix B.

## 2.3 Detail Design

Based on Kinefac's preliminary design, detail design of the machine was initiated. Several meetings were held between Keystone and Kinefac to ensure that the machine could be integrated with the part handling system and overall floor plan, being defined in the next task. Detail design review meetings were also held between all the concerned parties to ensure that the design would fulfill the specified machine requirements.

Efforts were also expended in establishing definitions of all the various sub systems required to support and operate this machine. These sub systems included RF and MF power supplies, marquenching oil heating and cooling systems, marquenching oil filtration system and the nitrogen atmosphere system. The details of mechanical, electrical and control system of the machine and the various sub systems are appended in Appendix C.

# 3. Task 2: Define Integration of Ausform Finishing Machine in P/M Gear Production

Three distinct issues were addressed in this task. The first related to the actual part handling to load a part on to the ausform finishing machine and unload the finished part off the machine. Interaction between the machine and the part handler becomes more complex as the controlled nitrogen atmosphere has to be retained when the part is being inserted and removed from the machine. The second issue related to defining the actual location of the machine and its sub systems on the production floor at KPM. This was addressed in two situations, one related to the machine in a pilot facility and the second on its integration into a production facility. The third issue of machine integration dealt with defining the human-machine interface through the visual display of the machine controller. In all these three issues, safety related aspects of integrating this machine were also addressed. This effort was conducted in two sub tasks, as described below.

## 3.1 Preliminary design

Based on the preliminary design of the machine the load and unload locations were identified. Since meshing the gear with the rolling die, after induction heating is a requirement, different options of accomplishing this were considered. Also in consideration is the need to maintain an inert (Nitrogen) atmosphere within the processing chamber of the machine in order to minimize any contamination forming on the part surface during induction heating. Locating the tooth and space on the part as it is gripped by the induction heating/roll finishing spindle in a specific orientation, retaining this location through the induction heating cycle and rotating the rolling dies to match that orientation when meshing is required, was considered the most feasible strategy to fulfill this requirement. A preliminary floor plan was also defined with anticipated subsystems (quench oil, hydraulics, power supplies, etc.) located on KPM's floor. At this stage KPM was of the opinion that this machine would be a stand alone and while it was considered amenable to standard work material transfer ("blue steel" chutes for example) from other P/M processing equipment, no further effort was expended in defining this aspect of the machine integration.

3.2 Detail design

Based on the definitions and requirements specified in the preliminary design a part handling system, that fulfills insertion and removal of the gear being processed and enables the part-roll die meshing, was defined. The finalization of the various sub systems and required electrical enclosures resulted in a final version of the Floor Plan and two versions, that situate the machine in a pilot facility and in a production facility, were designed. The human machine interface "screens" that will be displayed on the visual display of the machine controller were also defined. Operational safety aspects of the machine were taken into consideration in all aspects of machine integration. All details of machine integration are appended in Appendix C.

## 4. Task 3: Optimize Process for P/M gears

In this task efforts were focused on optimizing the rolling die geometry to improve the tooth form on both the Standard test gear and the Focus gear, from what was obtained in Phase I of this project. Two further versions of the Standard test gear were also considered. These are gears made from the carburizing grade (P/M 4620) but without the densification process of hot forging and another version of hot forged P/M 4620 but prepared for treatment after ausform finishing which is anticipated to yield a higher bending strength. While the Standard test gears in these two categories are currently available, no ausform finishing has been conducted on them for further strength and durability evaluation, because of Phase II time and budget constraints. This could be accomplished in Phase III. The results obtained on the rolling die geometry optimization effort are presented below.

4.1: Standard test gear optimization:

The profile and leads obtained on the P/M 4620, Carburized and hardened, Standard test gear, after ausform finishing, at the end of Phase I of this project, are illustrated in figure 1. While the total tooth profile error, $F_{\alpha T}$, on the drive side (top half of the profile chart) is within +/-0.0003 inch (indicating a quality level of A7 as per ANSI/AGMA 2015-1-A01) the profile on the coast side (lower half of the profile chart) is poor. The lead obtained is a well crowned straight lead with a total lead tolerance, $F_{\beta T}$ is within +/-0.0002 inch and acceptable (quality level A6). Figure 2 shows the tooth spacing errors on the spur gear before (top figure) and after ausform finishing. While total index error (cumulative error) is not significantly impacted, the max tooth to tooth error is reduced (from 0.0005 inch before to 0.0002 inch after). Owing to budget and time constraints further rolling die development and optimization was suspended in Phase I and the gear tooth tested for strength and durability with test loads applied only to the drive side of the gear tooth.

Further efforts in Phase II were directed at optimizing the die profile in order to obtain improved profile accuracy on the drive and coast side of the teeth on the Standard test gear. Figure 3 shows

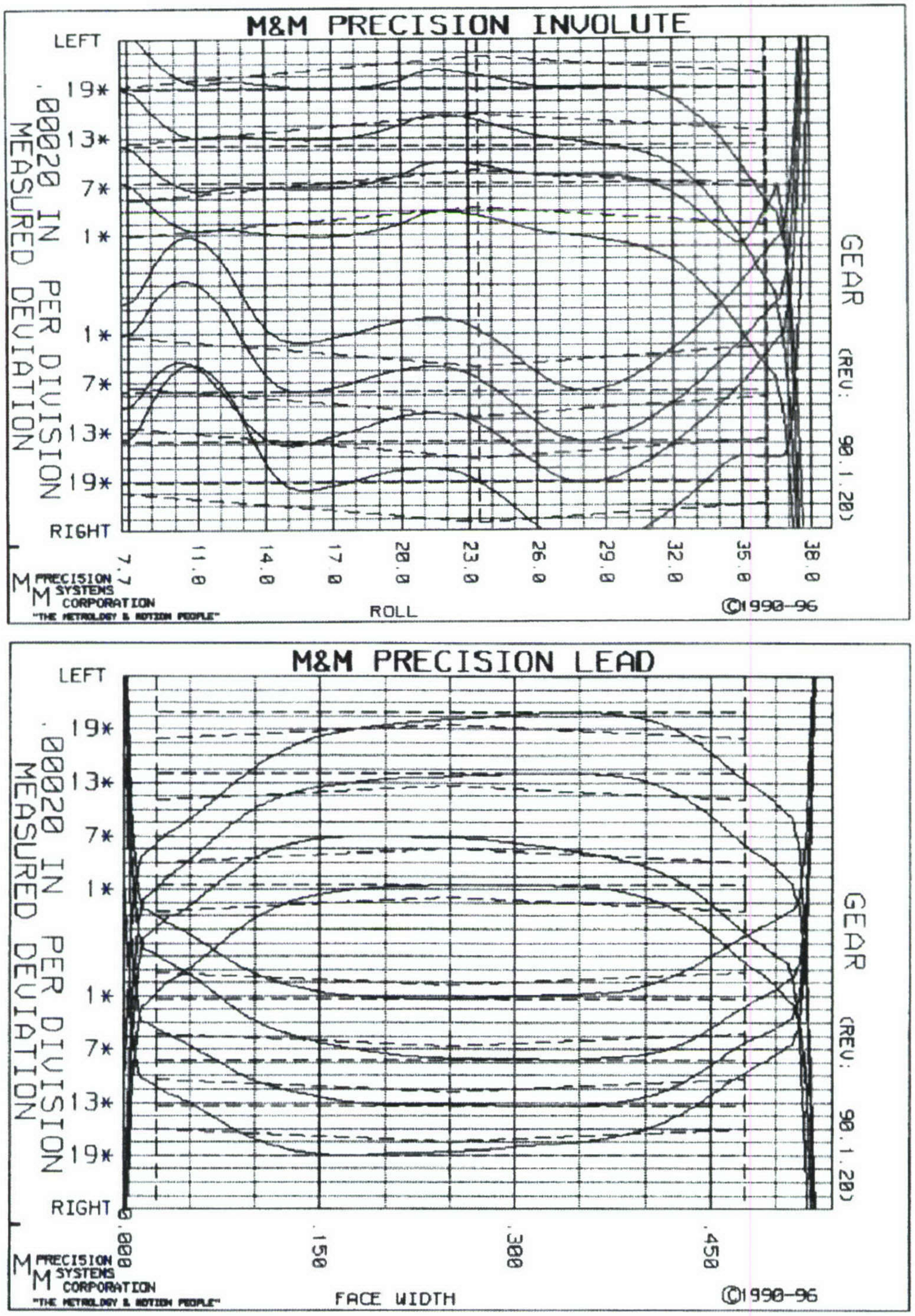



**Figure 1: Profile and Lead charts on ausform finished Standard test gear (grind 2)**

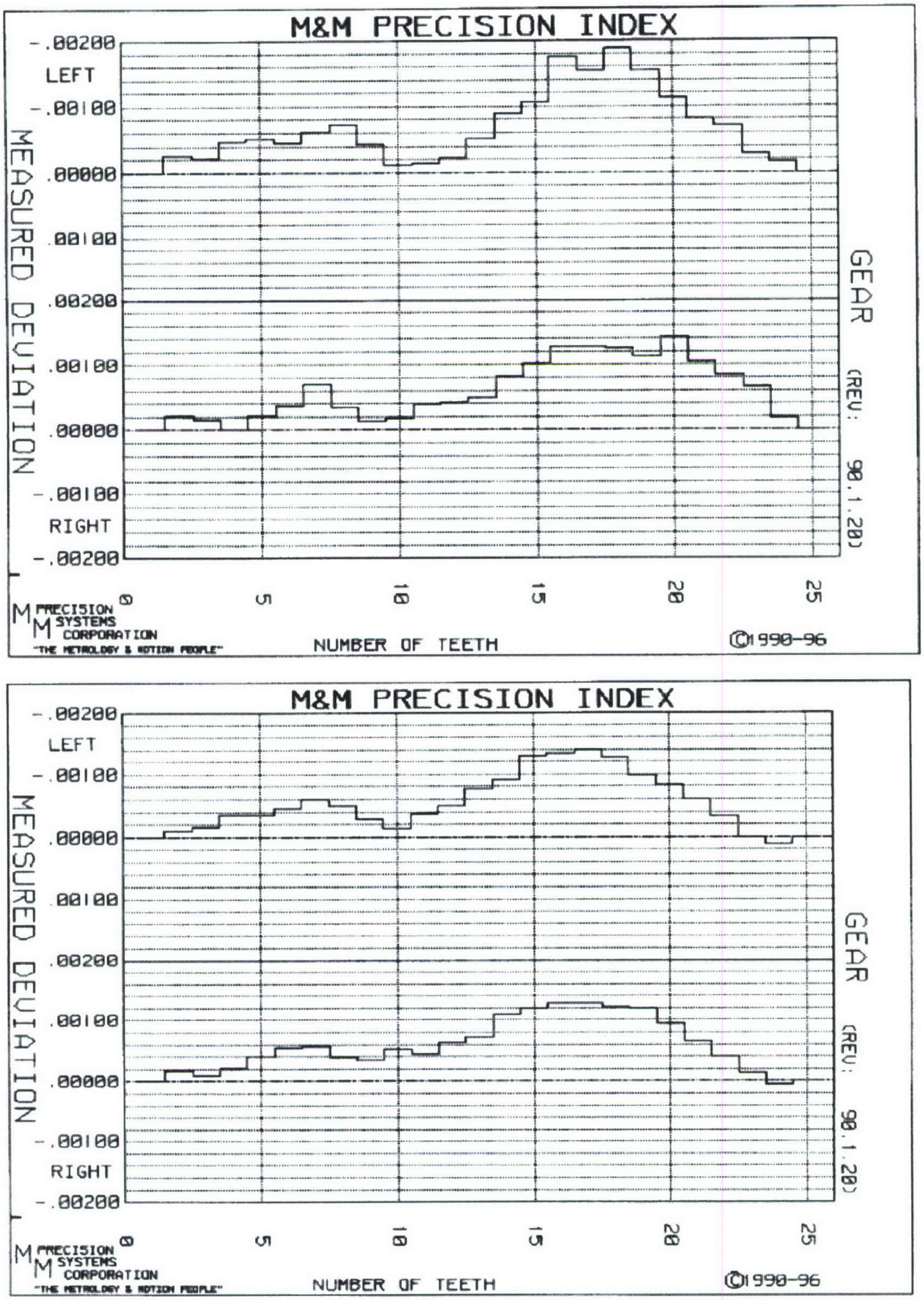
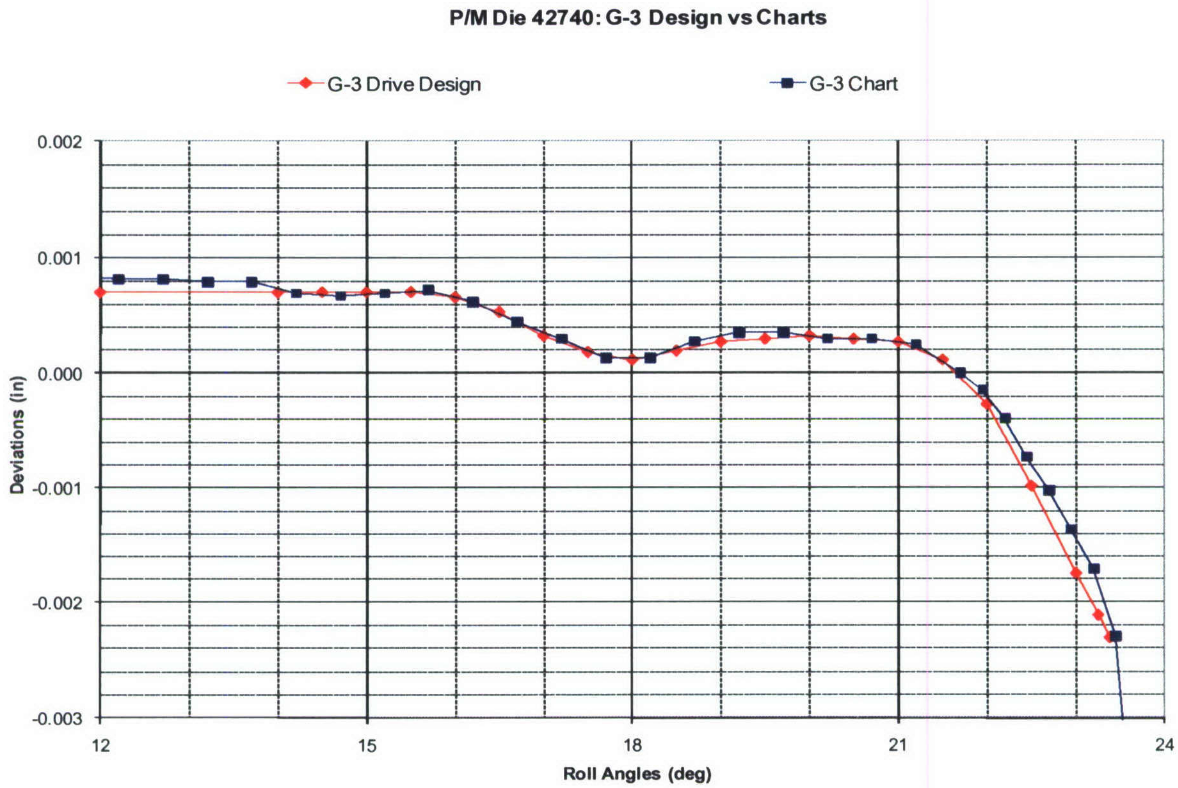



**Figure 2: Tooth spacing errors before and after ausform finishing**



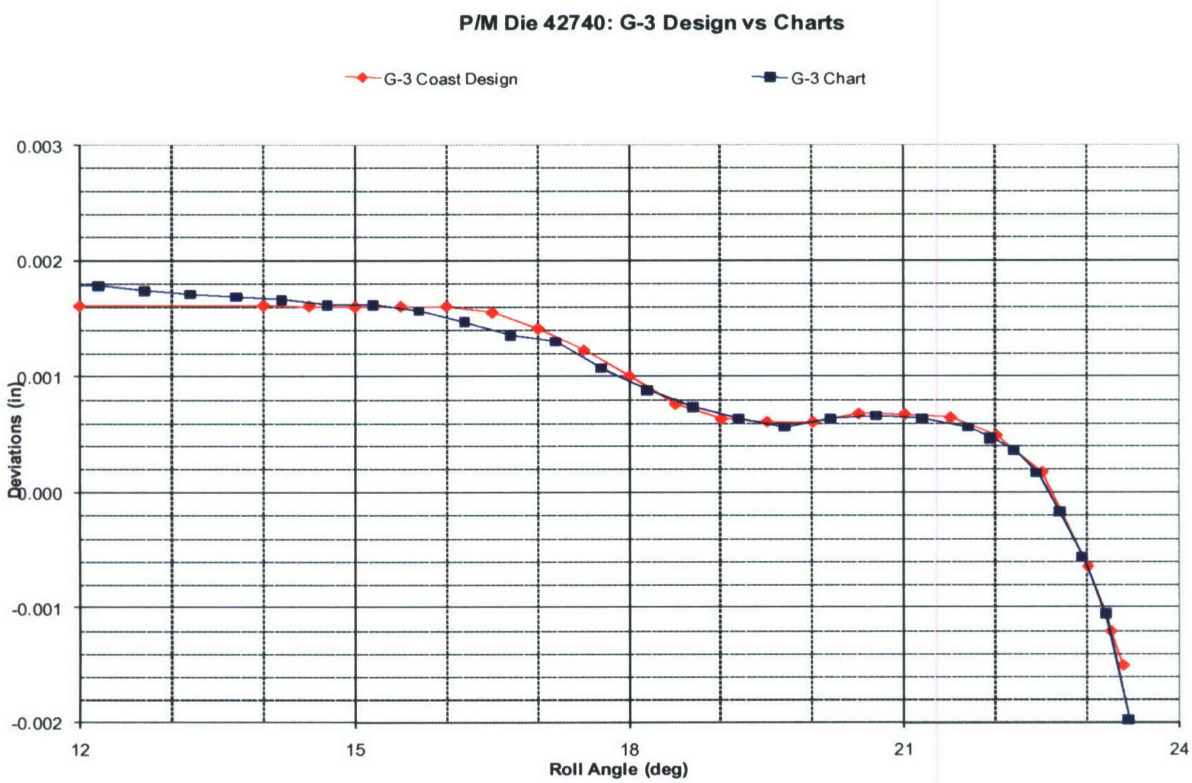




**Figure 3: Desired and actual rolling die tooth profiles for drive and coast (grind 3)**

the desired and actual rolling die tooth profiles for the drive and coast side. The desired profile is derived empirically since the existing die profile prediction model is available only for wrought materials. The extension of these analytical models to consider P/M materials will be addressed in Phase III.

The resulting profiles obtained on the ausform finished Standard test gear, utilizing the rolling dies with the profiles illustrated in figure 2, are illustrated in figure 4. A comparison of the profiles in figure 1 and 3 reveals a significant improvement in the profile on the coast side. The major (+/-0.0006 inch) undulations have been reduced to less than +/-0.0003 inch, while the drive side exhibits an acceptable but increased crown of about 0.0004 inch. Since the coast side still exhibits a 0.0003 inch concave feature (hollow), another iteration of die profile optimization was considered.

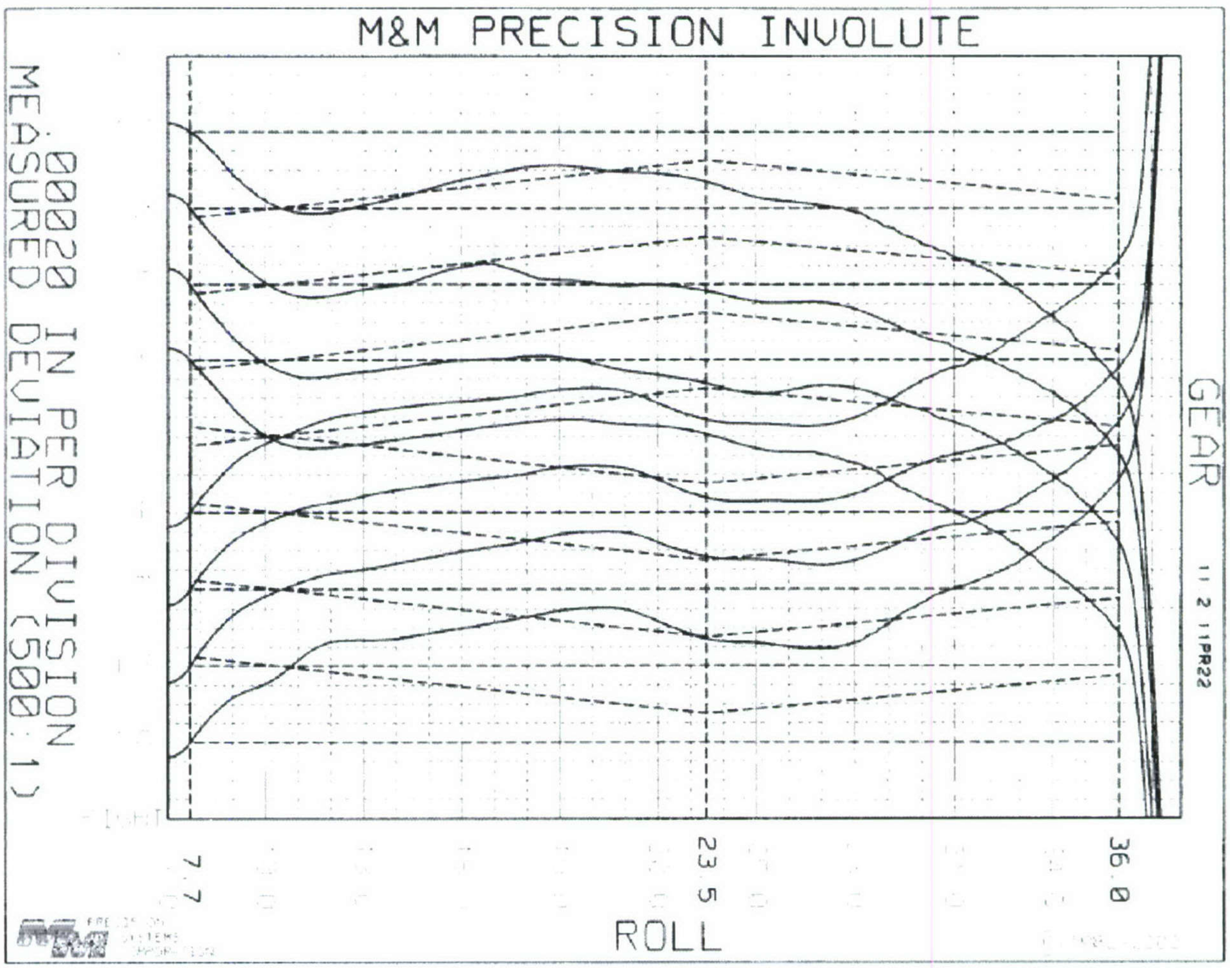
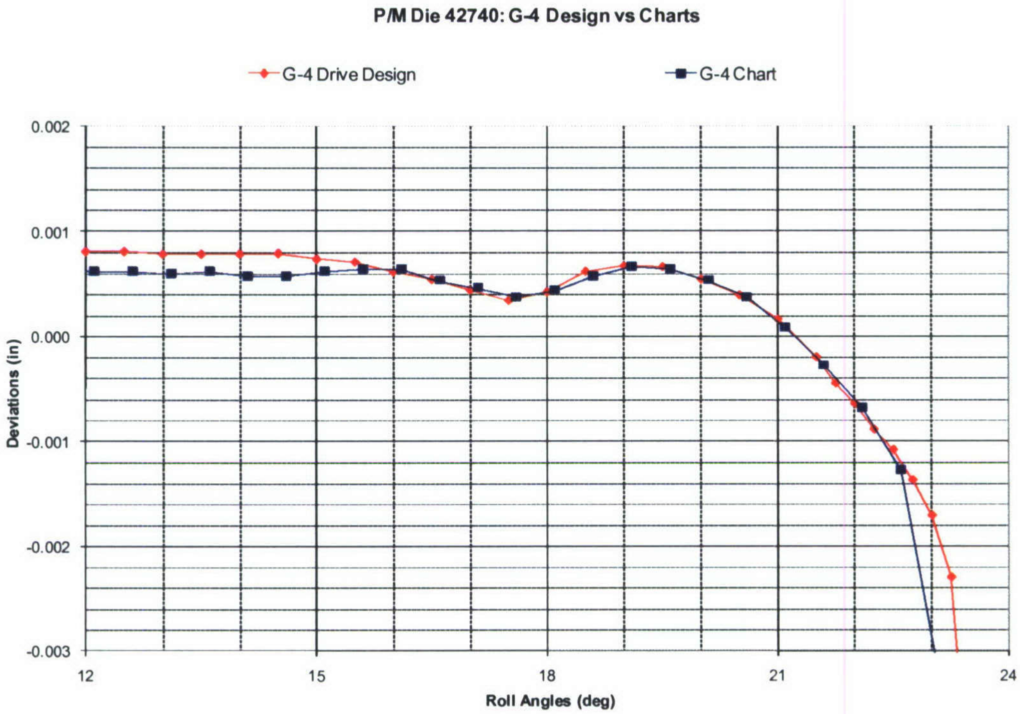



**Figure 4: Gear tooth profiles on ausform finished, Standard test gear (grind 3)**

Figure 5 illustrates the desired and actual rolling die tooth profiles for the next iteration (grind 4). The tooth profiles obtained on the P/M ausform finished, Standard test gear with these die profiles is illustrated in figure 6. A slight improvement (reduction of crown on the drive side and



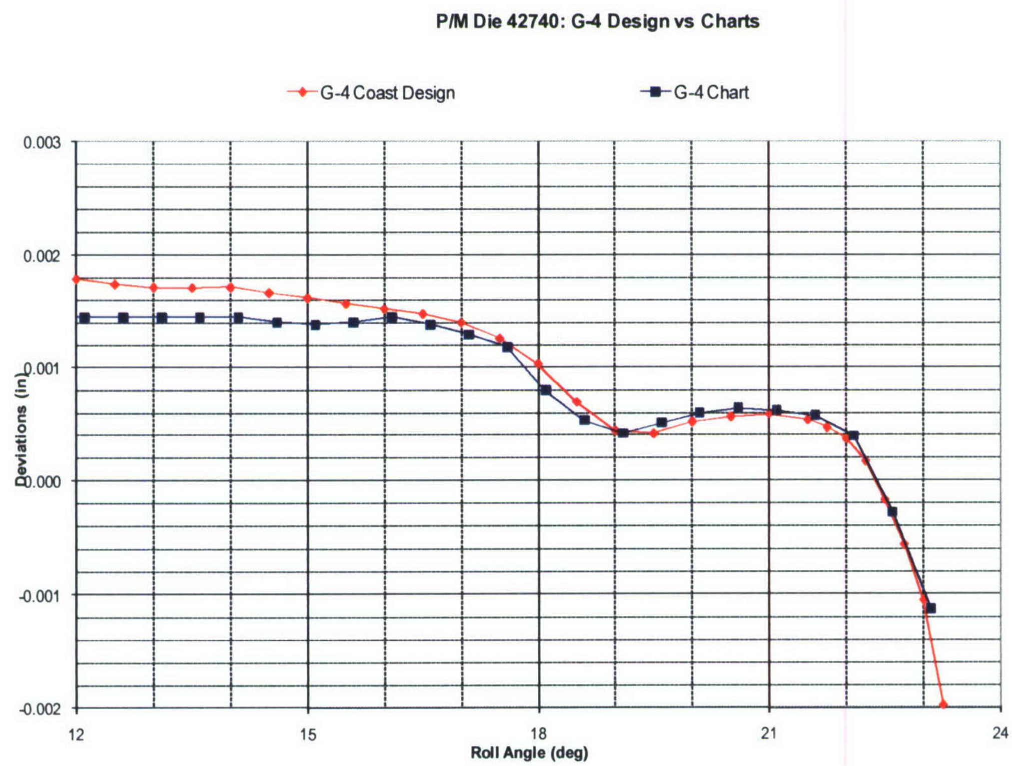




**Figure 5: Desired and actual rolling die tooth profiles (grind 4)**

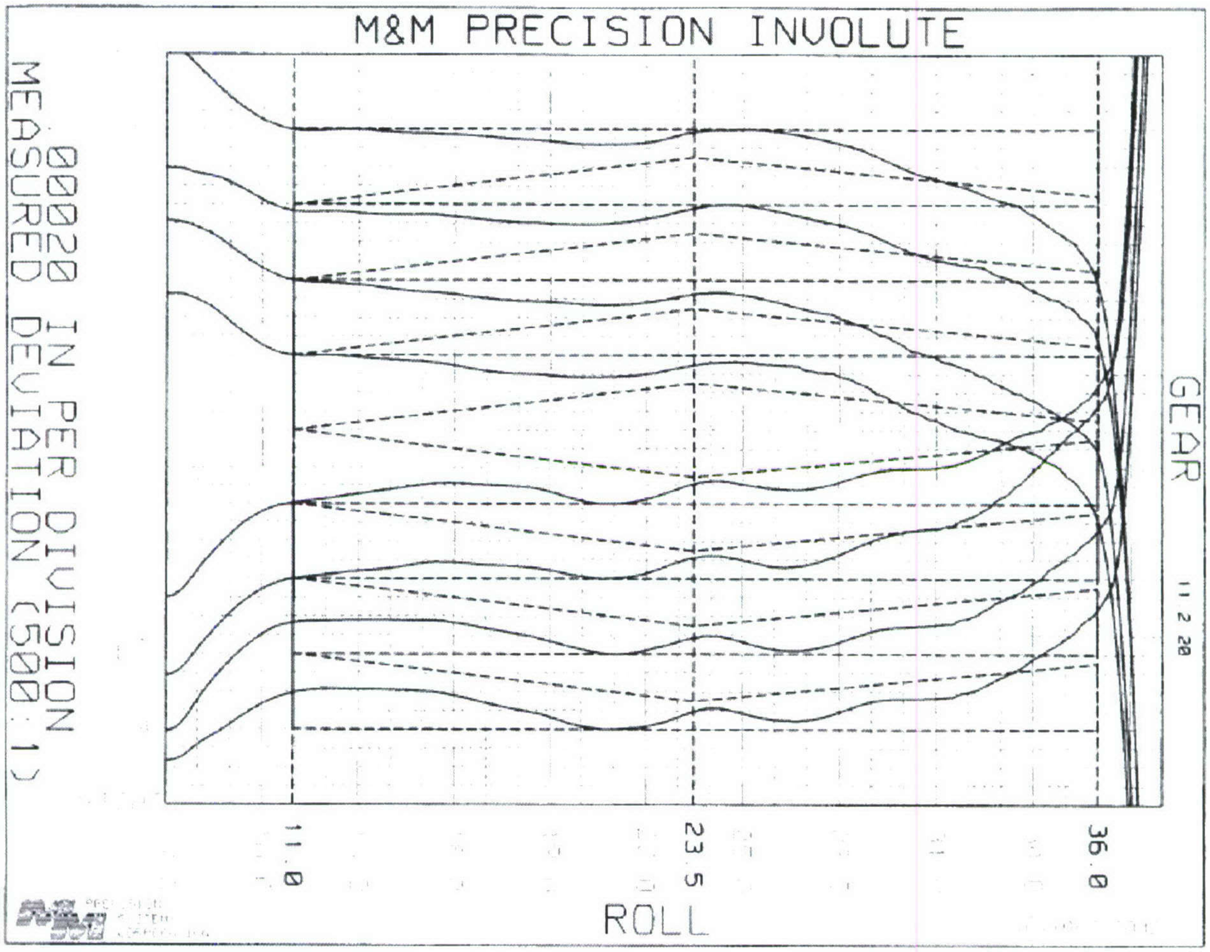



**Figure 6: Gear tooth profiles on ausform finished, Standard test gear (grind 4)**

a reduction of the hollow on the coast side) is observed. While one more iteration would probably be sufficient to further straighten the profile, this iterative effort was severely hampered by extremely long delays (as much as 5 months) at the rolling die manufacturer. Another concern that developed was the ability of the rolling die manufacturer to provide the profile modifications as requested because of the discrepancy between the desired profiles and the actual profiles produced. Consequently this effort of rolling die optimization was concluded and attention shifted to processing the Focus gear.

4.2: Focus gear optimization

The focus gear for this effort is New Process Gear transfer case planet gear, whose details are defined in table 1. Even though Phase I had indicated superior performance with the 4620 carburized and hardened alloy, this effort was expended in processing gears of both alloys (4620 and 4680) and on obtaining the appropriate metallurgical characteristics and gear tooth geometry. A detailed drawing of the focus gear is illustrated in figure 7.

Induction heating parameters: Since the ausform finishing process utilizes dual frequency induction heating, both MF and RF power and duration have to be iteratively developed, based on the hardness and hardness profiles obtained. Figure 8 illustrates the hardness profiles

| | |
|---|---|
| Number of Teeth | 19 |
| Diametral Pitch | 16 |
| Pressure Angle | 18.44 |
| Lead (RH) | 10.83 |
| Face Width | 1.4 |

**Table 1. Focus gear details**

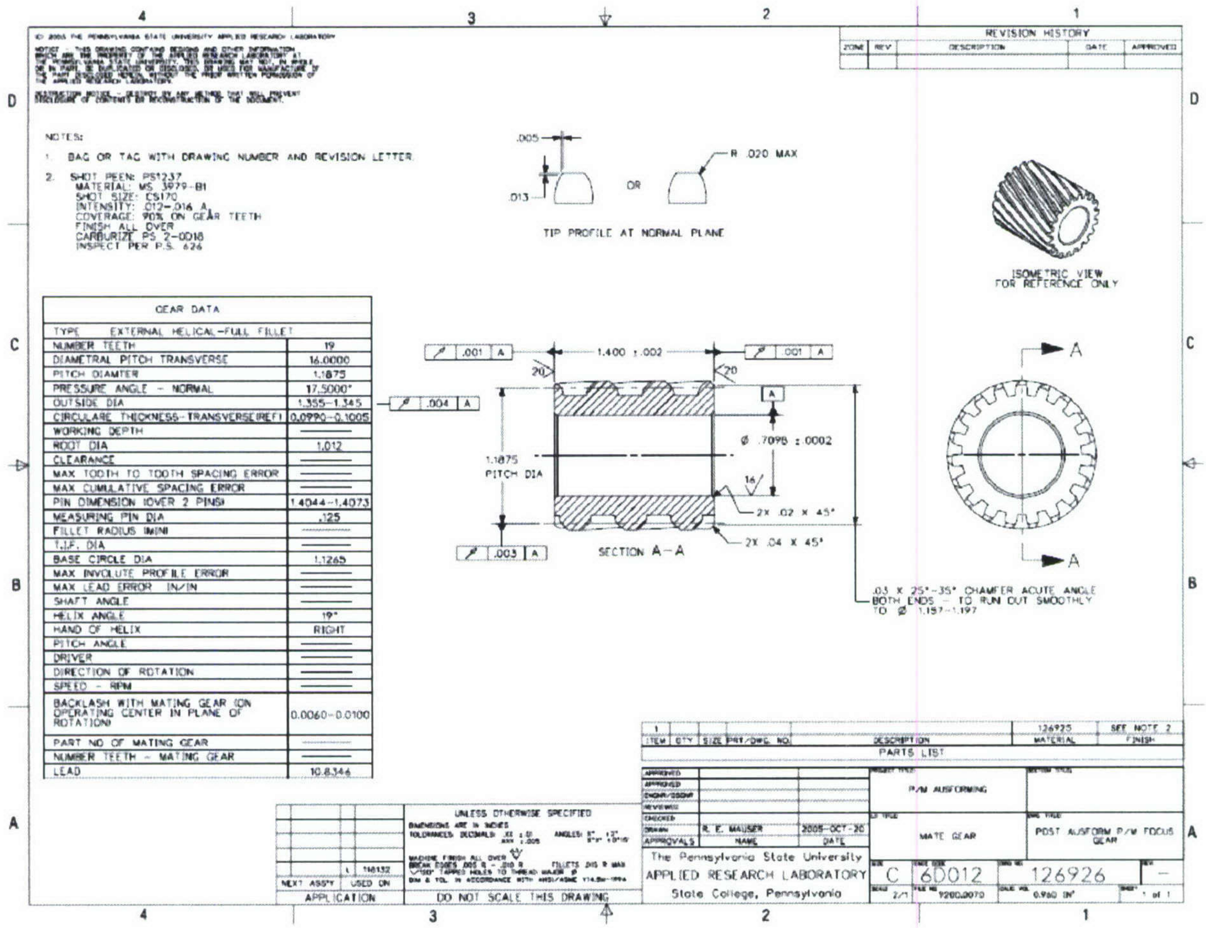


**Figure 7. Detail drawing of Focus gear**

obtained at the middle of the tooth (upper figure) and in the root fillet (lower figure). Serial numbers starting with the number 2 refers to the 4620 carburized and hardened alloy and serial 8 refers to the 4680 alloy. Since the 4620 gears were received in the carburized and hardened condition, induction heating parameters were developed to replicate the hardness profile of the pre-ausform gear, serial number 205 (green data points). The 4680 gears were received in an annealed condition so that the core was at about 30-35 HRc and the induction heating parameters developed to harden the surface to about 60-62HRc.

As can be seen from figure 8, various combinations of MF and RF parameters were successful in obtaining the required hardness profile at the mid tooth but only parameters associated with serial number 202 was acceptable at the root fillet. The selected induction heating parameters are defined in table 2.

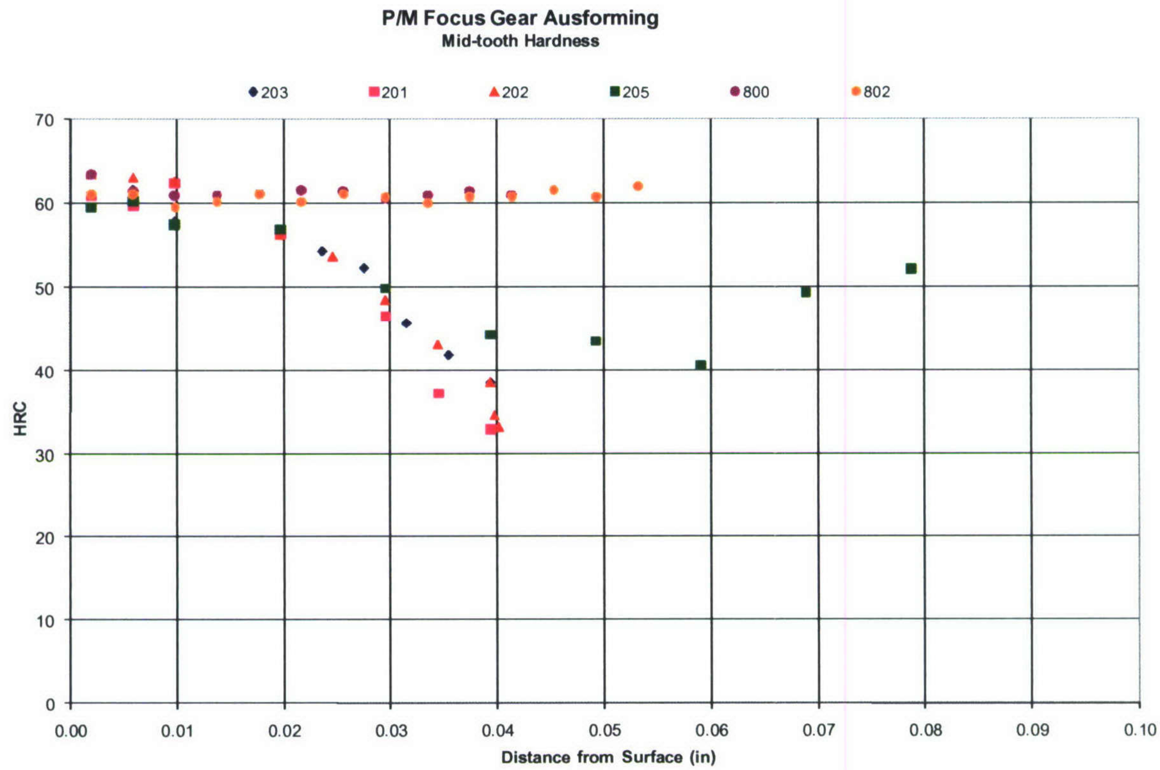
| Focus gear alloy | MF Power | MF time | RF Power | RF Time |
|---|---|---|---|---|
| P/M 4620 HF C/H | 70 kw | 2.5 sec | 90 kw | 0.5 sec |
| P/M 4680 HF | 30 kw | 2.5 sec | 90 kw | 0.5 sec |

**Table 2. Selected induction heating parameters**

Gear tooth profile: The pre-ausform finished parts of the two alloys had different sizes. The 4620 carburized and hardened alloy gears had a pre-ausform diameter over pins of 1.410 inch. +/-0.0005 and the 4680 alloy gears had a pre-ausform diameter over pins of 1.408 inch. +/-.0005. Utilizing a gear rolling die with the die tooth profile as shown in figure 9, the gear tooth profile obtained on the two alloys is illustrated in figure 10 (4620 alloy-upper figure, 4680 alloy-lower figure) . The finished diameter over pins for the 4620 and the 4680 alloy focus gears are 1.407 and 1.405 respectively.

While the gears of both alloys fall within the specified tolerance band for "over the pins" dimension the part (1.4044-1.4073) the significant slope of the profile on the 4680 gear (lower figure) is due to its smaller pin dimension that results form the fact that the pre-ausform part was smaller. The +-0.0002 inch undulation on the 4620 focus gear (upper figure) implies a slight modification to the die tooth profiles on both sides at the appropriate roll angles. The profiles are consistent. The fact that these profiles were obtained based on the first predicted die tooth profile, clearly establishes that a few iterations of die development would provide the desired tooth profile on the focus gear. Since the task of regrinding the die was too time consuming, efforts were focused on establishing the lead on the focus gear.

Gear tooth lead: Helical gears had never been processed on the double-die ausform finishing machine and some time was expended in understanding the impact of the various machine settings on the lead of the helical gear. In order to speed up the process of establishing the machine setting, a batch of 4680 focus gears was annealed to 20 HRc and roll finished in a manner to simulate "cold rolling" (without induction heating or marquenching) as it is practiced in industry. This avoided the time consuming task of heating the marquenching oil and speeded up the experimental iterations. Also, since "cold rolling" is widely and satisfactorily practiced in industry, the relationship between what is obtained on the Penn State, double-die machine in cold rolling and ausform finishing would be of tremendous significance.



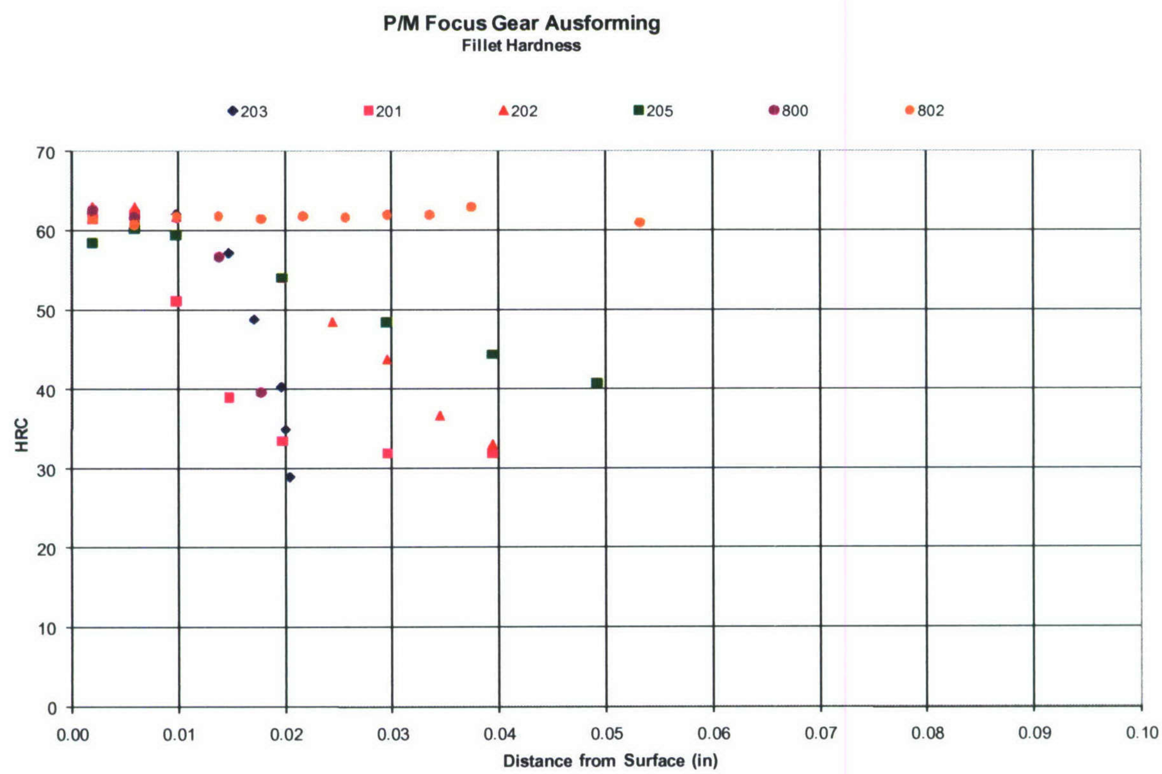
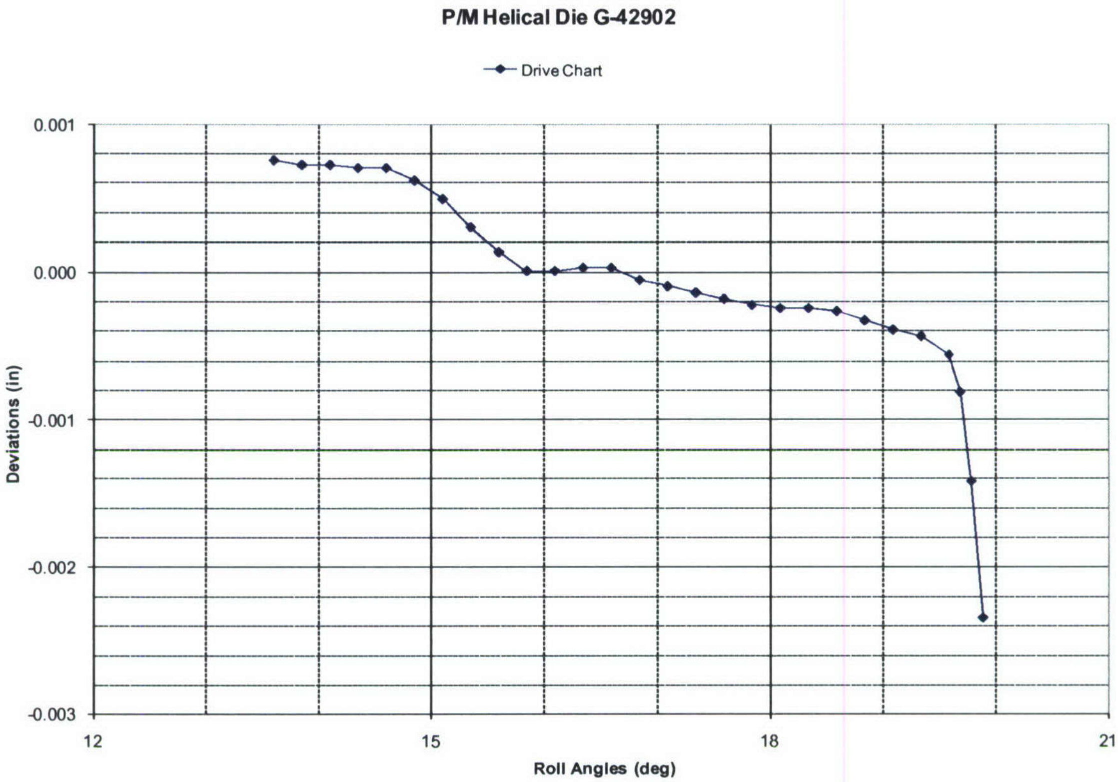




**Figure 8. Hardness profiles for focus gear**



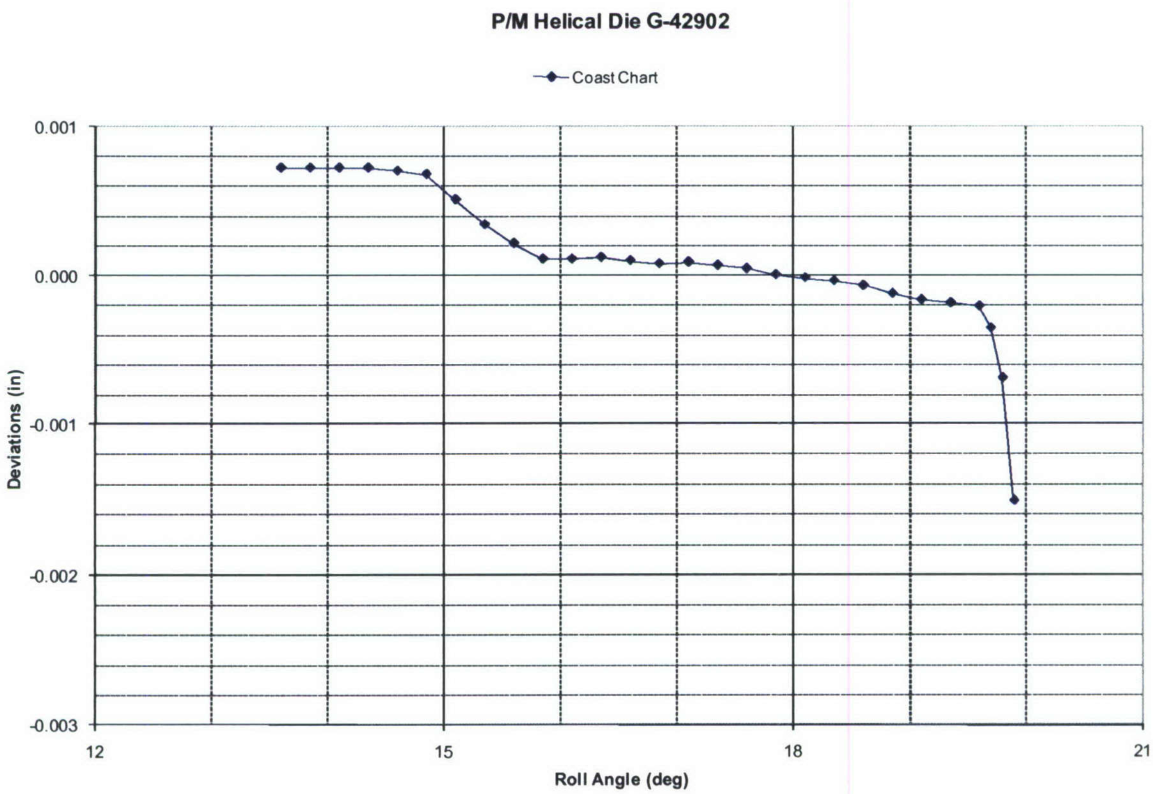
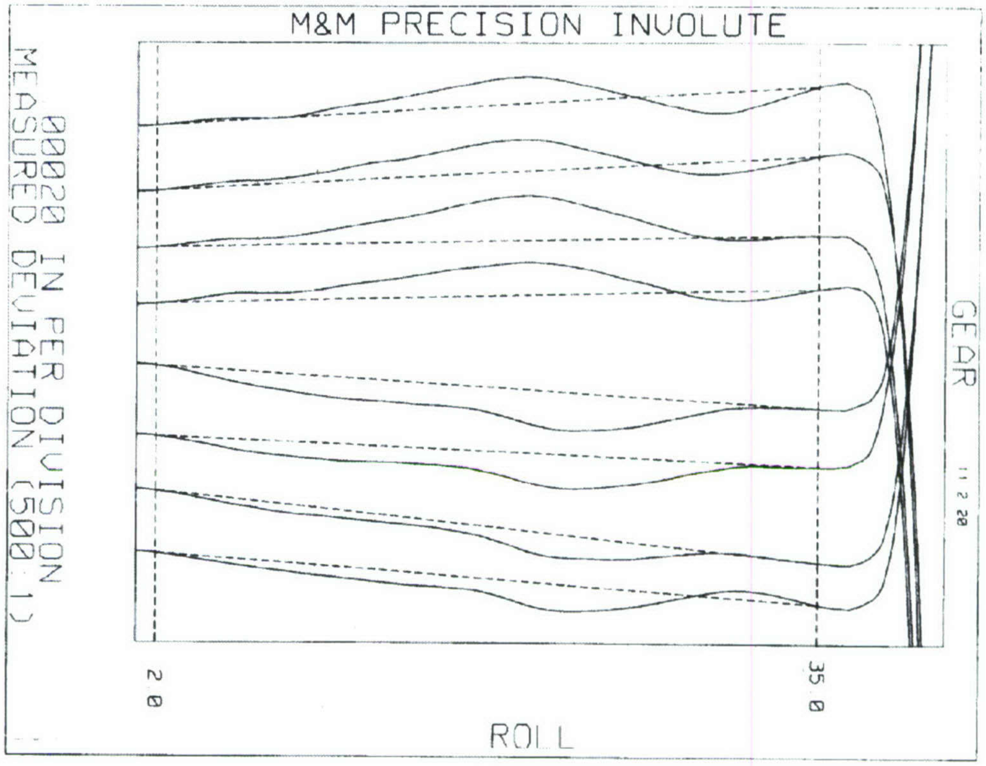




**Figure 9. Rolling die tooth profiles for focus gear**



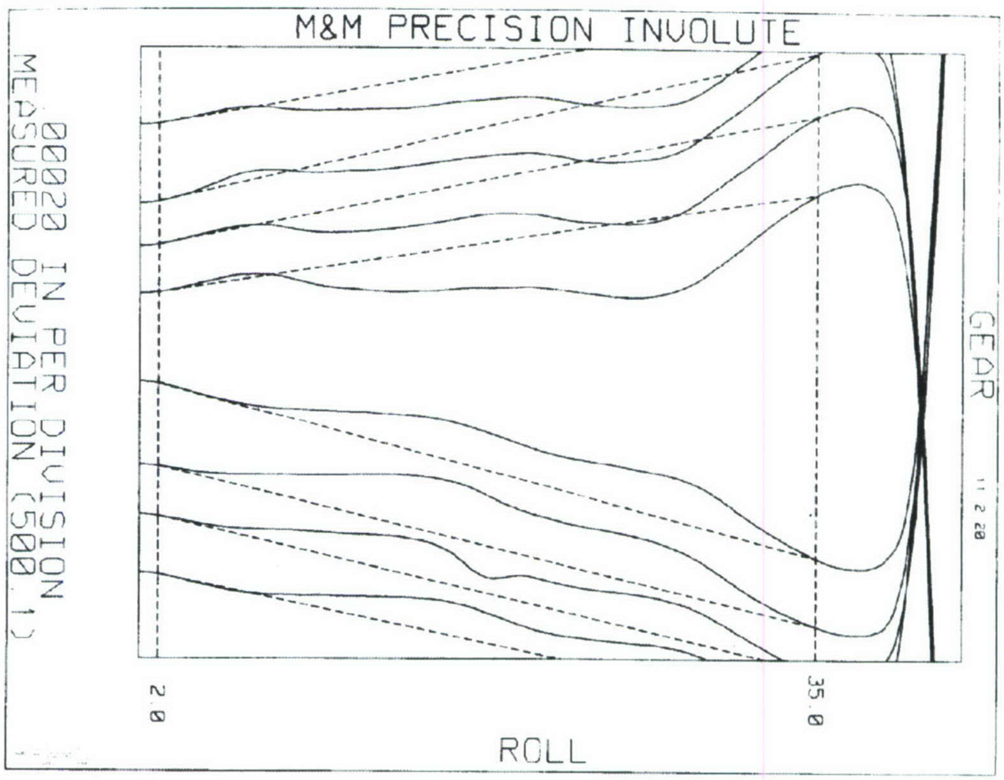




**Figure 10. Gear tooth profile for focus gear**

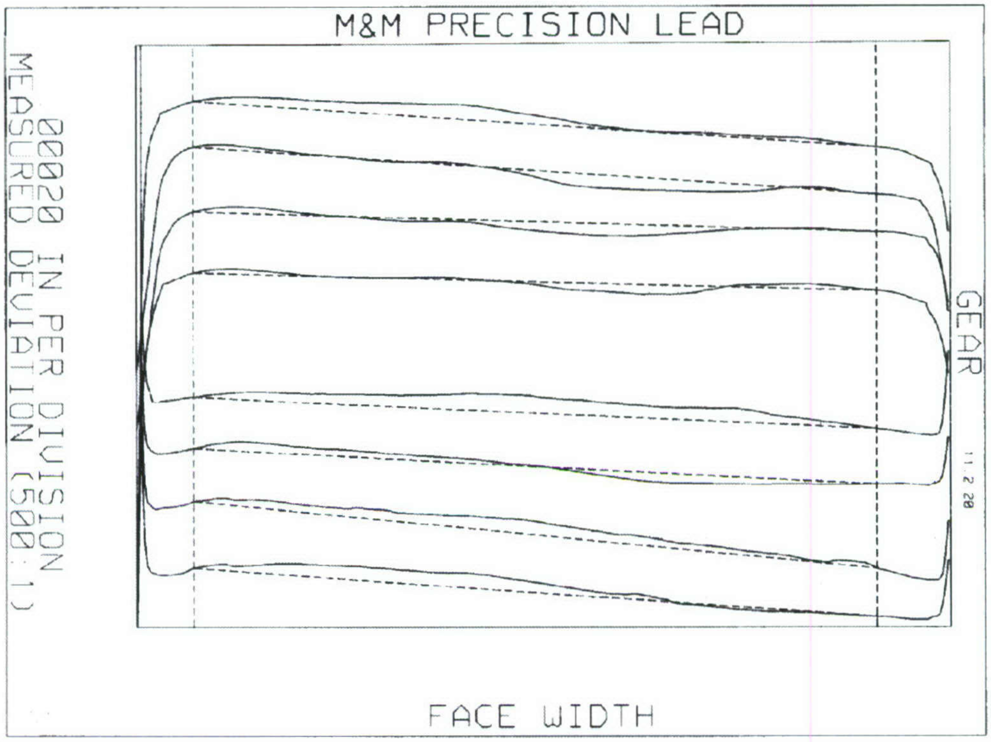



**Figure 11. Leads on "Cold Rolled" focus gear**

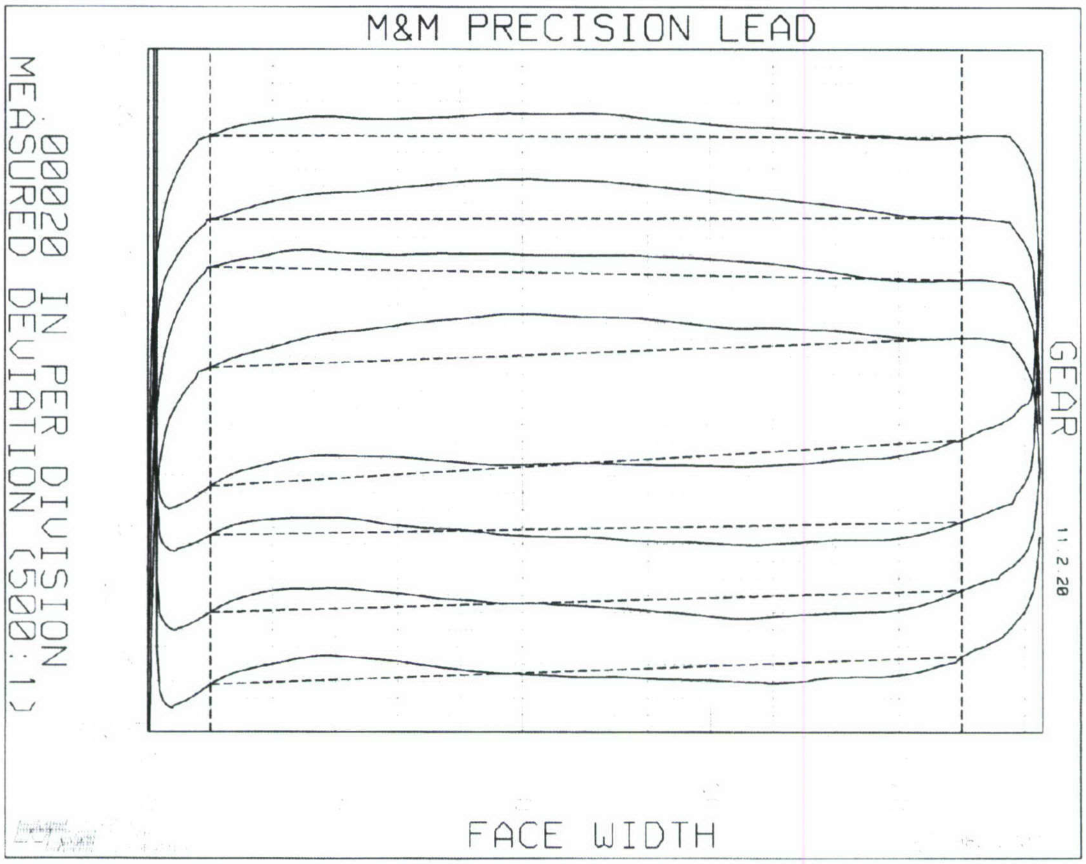



**Figure 12: Leads on an ausform finished focus gear**

In spite of many attempts the best obtained "cold rolled" leads on the focus gear are illustrated in figure 11. The feature of concern is the 0.0002-0.0003 inch hollow on the drive side of the tooth (upper half of the figure) and a similar hollow on the coast side of the tooth (lower half of the figure). Of further concern is the 0.0002-0.0003 inch protuberance in the lead at the left hand of the coast side of the gear tooth. Even though a total lead error $F_{\beta T}$ for this gear is 0.0006 inch for an A7 gear quality, this is not acceptable in production and a significantly crowned condition should exist at the ends of the teeth.

Various settings of the two angular rolling die axes adjustments (into the work gear axis and perpendicular to that direction) and phase adjustments between the die teeth and the gear teeth were attempted, with deterioration in the lead but no effect on the issues identified as concerns. At this stage it was decided to ausform finish the focus gear, with a minor adjustment to compensate for the lead slope in figure 11.

Figure 12 illustrates the leads obtained on an ausform finished 8620 alloy focus gear. While the slope has been improved the hollow condition appears to have been amplified in the range of 0.0003-0.0004 inch. A close examination of the ausform finished leads indicates that the leads obtained in the "cold rolling" are modified by the traditional "crowning" effect of ausform finishing (figure 1). Several iterations of angular adjustments and phasing adjustments did not improve the situation.

It is likely that some alignment in the machine axes may be the cause of the observed hollow in the lead. The fact that this is prevalent in both cold rolled and ausform finished gears lends credence to this possibility. Further investigations to improve the lead would be considered in the follow on phase of work.

**5.0 Conclusions**

The three tasks proposed in this phase were substantially completed. Specifically, task 1 and task 2 in establishing a design of the design of the P/M ausform finishing machine and its integration to a production line including automation for part handling were competed. Optimizing the ausform finishing process was substantially advanced for both the standard test gear and the focus gear. Ability to control test gear and enhance the profile accuracy was demonstrated, up to AGMA quality A7 but because of the inordinate amount of time required to re-grind the rolling die to obtain the desired profiles, this was not completed to level that has been achieved in past projects (quality level A5). While good leads were obtained on the standard test gear (spur), the quality of leads obtained on the focus gear (helical) needs to be improved. The unacceptable lead related features on the focus gear are present in the "cold rolled" and ausform finished gears. This implies that a machine alignment issue (coaxiality of the two rolling die assemblies or other issues) may be the cause. This will be explored and corrected in the follow on phase (phase III) of the project.

## References


1. *Powder Metallurgy design Manual*, 2nd ed, Metal Powder Industries Federation, 1995.
2. Esper, F. J. and Sonsino, C. M., *Fatigue Design of PM Components*, European Powder Metallurgy Association, 1994.
3. Breur, D. J., *Utilization of Powder Metal and Shot Peening Residual Stresses to Maximize Cost and Performance Benefit of Highly Loaded Gearing*, Gear Technology, Nov/Dec 2005.
4. Lawcock, R., Buckley-Golder, K., and Sarafinchan, D., *Testing of High Endurance PM Steels for Automotive Transmission Gearing Components*, SAE Technical Paper 1999-01-0293, 1999.
5. Jones, P., Buckley-Golder, K., Lawcock, R., and Shivanath, R., *Densification Strategies for High Endurance P/M Components*, The International Journal of Powder Metallurgy – Volume 33, No. 3, 1997, p 37-44
6. Lawcock, R., *Rolling Contact Fatigue of Surface Densified Gears*, Advances in Powder Metallurgy & Particluate Materials, 2005, Part 10, pp. 72-89.
7. Mandel, J., Draxler, G and Geiman, T., *Evaluation of Scuffing Resistance of Powder Metal Gears in the FZG Back to Back Test Rig*, Advances in Powder Metallurgy & Particluate Materials, 2005, Part 11, pp. 43-57.
8. Sonsino, C. M., Lipp, K., *Rolling Contact Fatigue Properties of Selected PM Materials for Gear-Box Applications*, SAE Technical Paper 1999-01-0333, 1999.
9. Hoffmann, G., Sonsino, C., and Michaelis, K., *Rolling Contact Fatigue – Component Design and Testing for P/M Applications*, SAE Technical Paper 1999-01-0332, 1999.
10. Yoshida, A., Ohue, Y., Karasuno, I., *Comparison of Surface Durability & Dynamic Performance of Powder Metal and Steel Gears*, Gear Technology, September-October, 1995, pp 18-23.
11. Freidhoff, T. G., Spirko, J. R., Delozier, M. R., and Sanderow, H., I., *Surface Fatigue of P/M Iron-Nickel Steel*, Proceedings of MPIF PM$^2$TEC'96, Washington D.C., 1996.
12. Cadle, T., Landgraf, C., Brewin, P., and Nurthen, P., *Rolling Contact Fatigue Resistance of P/M Steels – Effects of Sintering Temperature and Material Density*, Advances in Powder Metallurgy and Particulate Materials – 1991, MPIF, 1991, p 175-182.
13. Prucher, T. and Sanderow, H., *Surface Fatigue of P/M Alloys*, Advances in Powder Metallurgy and Particulate Materials – 1994, Vol. 2, MPIF, 1994, p 99-111.
14. Mars, O., Jacobson, O., Axelsson, B., Kuyenstierna, C., Klocke, F., Strehl, R. and Escher, C., *Contact Fatigue Properties of Some Low Alloyed Sintered Steels*, presented at Euro PM'95, Birmingham, England, Oct., 1995.
15. Hoffmann, G. and Jandeska, W., *Effects on Rolling Contact Fatigue Performance*, Gear Technology, Jan/Feb 2007.
16. Hoffmann, G. and Jandeska, W., *Effects on Rolling Contact Fatigue Performance – Part II*, Gear Technology, Mar/Apr 2007.
17. Queeney, R. A., Kuplen, S. T., Amateau, M. F., Sonti, N., *Mechanical Response of Surface-Ausrolled Sintered Steel*, Advances in Powder Metallurgy – 1991, vol 3, pp 159-170.
18. Kuplen, S. T., Amateau, M. F., Sonti, N., and Queeney, R. A., *Ausrolling Sintered Steels for Bearing Elements*, Advances in Powder Metallurgy – 1992, vol 2, pp 355-363.

19. Sonti, N., Puskar, J., and Queeny, R. A., *A Case Study in Ausformed Helical Pinion Gear*, Advances in Powder Metallurgy – 1996, vol 4, pp 451-461.
20. Puskar, J., Stoudt, G. L. and Queeny, R. A., *Microstructure and Mechanical Response of Ausformed Steel Surfaces*, Advances in Powder Metallurgy – 1996, vol 4, pp 491-500.
21. E. M. H. Lips and H. Van Zulien, *Improved Hardening Techniques*, Metal Progress, 10/1954.
22. D. J. Schmatz and V. F. Zackay, *Mechanical Properties of Deformed Metastable Austenitic Ultra High Strength Steels*, Trans. ASM, 1959.
23. V. F. Zackay and, Strengthening Mechanisms in Solids, 1960.
24. E. B. Kula and J. M. Dhoshi, *Effect of Deformation Prior to Transformation on the Mechanical Properties of 4349 Steel*, Trans. ASM, 1960.
25. G. Thomas, D. Schmatz and W. Gerberich, *Structure and Strength of Some Ausformed Steels*, High Strength Materials, ed. V. F. Zackay, John Wiley & Sons, 1964.
26. E. N. Bamberger, *The Effect of Ausforming on the Rolling Contact Fatigue of a Typical Bearing Steel*, Trans ASME, J. of Lub. Tech., 1/1967.
27. E. N. Bamberger, *The Production, Testing and Evaluation of Ausformed Ball Bearings*, US Navy Contract NoW-65-0070-f, 6/1966.
28. U. S. Patent 6,779,270 dated 2004.
29. U. S. Patent 6,264,768 dated 2002.
30. U. S. Patent 6,126,892 dated 2000.
31. U. S. Patent 6,007,762 dated 1999.
32. U. S. Patent 5,799,398 dated 1997.
33. U. S. Patent 5,656,106 dated 1997.
34. U. S. Patent 5,451,275 dated 1995.
35. U. S. Patent 5,391,862 dated 1995.
36. U. S. Patent 5,221,513 dated 1993.
37. Rao, S. B. and McPherson, D. R., *Mechanical testing of Gears*, ASM handbook, vol. 8, 2000.
38. Sonti, N and Rao, S. B., High *Strength P/M Gears for Vehicle Transmissions-Phase I*, U.S. Army TARDEC/NAC, Technical Report No. 07-008, May 31, 2007.
39. *Accuracy Classification System-Tangential Measurement on Cylindrical Gears,* ANSI/AGMA 2015-1-A01.

**Appendix A**
**Contract No. N00024-02-D-6604, Task Order 0317**
**T.D. #4101093**
**High Strength P/M Gears for Vehicle Transmissions-Phase II**
(ARL/Penn State Project No. 13964)

*Task 1: Establish Design for Gear Ausform Finishing Machine*

## Production Ausform Gear Finishing Machine - Preliminary Requirements

Background

ARL Penn State in collaboration with Keystone Powdered Metals, Inc. is under contract with US Army TARDEC/NAC, to develop the capability to produce high strength powdered metal (P/M) vehicle gears with performance characteristics equivalent to conventional wrought steel gears. One of the primary tasks in the ongoing Phase II of the project entitled "High Strength P/M Gears for Vehicle Transmissions" is to develop a conceptual design of a production ausform gear finishing machine capable of producing ausform finished high strength P/M planetary pinion gears for the HMWVV. This document describes equipment requirements, and specifications for the proposed production ausform gear finishing machine.

Ausforming Process Description

Ausforming is a modified heat treatment process wherein the final quenching operation during heat treatment is interrupted above the $M_S$ temperature, as is done in marquenching. The steel in metastable austenitic condition is then plastically deformed, and finally cooled to martensite, resulting in increased strength. Requirements in steel to be ausformable are (a) presence of carbide formers, and (b) carbon content greater than about 0.6% by weight. The process is therefore applicable to carburized low alloy steel, as well as high carbon low alloy P/M steels.

Ausforming as applied to gear finishing is limited to surface layers of the gear teeth. Figure 1 shows a schematic time-temperature-transformation diagram that describes the ausform gear finishing process, involving four specific processing sub steps. The production ausform gear finishing machine will be designed to perform ausform processing sub steps in a controlled manner per recipe established for any candidate gear. The four ausform processing sub steps are:

- Line a-b representing induction heating to austenitize the gear tooth surface layers
- Line b-c representing quenching into hot marquenching oil maintained at up to 475°F (about 50-100°F above the $M_S$ temperature of the steel). Steel at this stage is in metastable austenitic condition
- Line c-d representing plastic deformation of metastable austenite, thereby inducing the ausforming effects in the steel
- Line d-e representing final cooling to transform deformed metastable austenite to martensite.

## Ausform Gear Finishing Equipment Requirements

It is proposed to develop a production ausform gear finishing machine capable of processing automotive/vehicle transmission spur and helical gears with outer diameter in the range of 1 to 2", maximum face width of about 2", and tooth sizes ranging from about 8 to 24 diametral pitch (DP). The production machine will be capable of processing carburized wrought and P/M steel gears as well as high carbon P/M steel gears. Demonstration gear chosen for the production ausform gear finishing machine is the focus gear from Phase I of the program, and is a 19 teeth, 16 transverse DP, 17.5° normal pressure angle, 19° right helix angle, 1.4" face width helical gear.

Production ausform gear finishing machine will include a gear roll finishing machine with capability to ausform finish gears at processing temperature of up to about 475°F, gear induction heating equipment, an oil heating and recirculating equipment, servo-hydraulic equipment, and a process and machine controller that integrates various ausforming machine subsystems. Following sections describe the criteria and required specifications for the above subsystems to successfully ausform the specified range of gear sizes and shapes. A summary of machine specifications is provided in table 1.

### *1. Gear Roll Finishing Machine Requirements*

#### *a. Double Die Gear Roll Finishing*

A double die gear roll finishing arrangement will be used to process spur and helical gears, wherein the work gear is held in a fixed central vertical axis and the two diametrically opposing dies are fed laterally in with respect to the gear axis to achieve the relative displacement between the work gear and the rolling die axes, thereby resulting in plastic deformation of the gear tooth surface layers to roll finish gears. Figure 2 shows a schematic of gear rolling equipment for ausform gear roll finishing. With this double die arrangement, gear roll finishing will be achieved by symmetric infeed motions of the two roll finishing dies with respect to the work gear. Figure 2 also shows the vertical axially locating capability that is required for the work gear to be moved from the load position at the top to the MF heating, RF heating, into the quench oil tank and to the rolling location. The vertical locating movement of the gear is to be provided by the induction scanner which is described in later sections.

Rigid infeed carriages will support the two die assemblies, and the carriages will move laterally on pre-loaded rolling element bearings. The degree of deformation must be controlled to close tolerances by controlling the infeed motion of the two rolling dies to within ±0.0005".

As the die spindles will operate at high temperature in the hot marquenching oil, long term exposure of the machine elements, such as spindles, bearings, etc., to high temperatures will result in over tempering and loss of hardness. It is therefore desirable that these components are fabricated using high hot hardness steels, to ensure that these components retain their strength and operating characteristics over an extended period of time.

Adjustment capability is to be incorporated for axial, in-plane and out-of-plane adjustment of the two rolling die axes in order to ensure proper orientation of the dies with respect to the work gear at the operating load and temperature. Preferably, the machine design should allow these adjustments to be made and monitored remotely with the ausforming processing tank at operating temperature. The ausforming processing tank is to be designed to contain the two die assemblies and the work gear in marquenching oil for processing at up to 475°F, and contain the two die assemblies, infeed hardware, and the die axes adjustment mechanisms, thereby maintaining a thermally stable environment with minimal gradients.

The processing tank must have an enclosure with capability to provide inert gas protection allowing operation at up to 475°F. Without an inert gas protection, the maximum marquenching oil operating temperature is limited to 400°F. Figure 4 shows a schematic of the side view of the machine describing the proposed arrangement.

*b. Drive System for the Rolling Dies*

The drive system must be capable of driving the two dies and maintaining rotational alignment between the dies. For example, the system could use two separate servo-drive electric motors to drive the two dies from the top, with the rotational alignment between the dies achieved through electronically controlled coupled optical encoders, synchronized through an electronic gear box (EGB) as an integral part of the controller. Alternately, a single electric drive motor may be used, but would require a mechanical gear box to split the drive to the two dies. Such an arrangement will also require a mechanical phasing arrangement on one of the die shafts to rotationally align one die with respect to the other and flexible couplings to allow infeeding of the die drive shafts.

*c. Meshing the Gear and the Rolling Dies*

Automatic operation of the ausform gear finishing machine requires the induction heated and marquenched gear to be located and then engaged (meshed) with the two opposing dies, and this must be carried out in the marquenching oil at 475°F. Several alternative techniques are to be considered include;

- The induction spin/scan equipment utilizing a servo-drive motor for gear rotation, and with sensors to orient the gear to be in phase with the dies. This will involve additional instrumentation and control complexity
- Use steel or teflon meshing gears with shaped lead-in to mesh the gear (system currently used by ARL Penn State)
- Use spring loaded steel or other meshing gears with shaped lead-in to mesh the gear

*d. Control Functions for the Gear Roll Finishing Process*

The machine and process control functions required for the roll finishing subsystem include:

(a) load and/or position controlled infeeding of the dies to ausform finish the work gears to final dimensions.
(b) servo-drive controls to the dies with electronically coupled rotational phasing alignment.
(c) a prescribed algorithm for position controlled infeeding of the dies in conjunction with the axial movement of the gear for meshing with the dies, depending on the type of meshing technique used.

### *2. Induction Heating System Requirements*

Induction heating equipment required for the ausform gear finishing machine includes the following:

- o induction power supply
- o output heating station including output transformer, capacitor bank for tuning the output circuit, and induction coil.
- o Induction spin/scanner equipment spinning and locating the gear through the MF and RF heating coils, and then to the rolling position in the ausforming processing tank.

#### *a. Induction Heating Equipment*

The first step of ausform gear finishing process is to austenitize the surface layers of the gear teeth including the root/fillet regions. Although only a single frequency MF power supply is planned for initial implementation for the focus gear, the production ausform gear finishing machine is to be designed to accept a Dual Frequency Induction Heating system, particularly the mechanical hardware to be located in close proximity including the induction scanner and the MF and RF output heat stations.

#### *b. Induction Scanner*

The functions of the induction scanner are (1) to rotate the gear at prescribed rpm during induction heating, as well as for meshing with the rolling dies, and (2) to traverse and locate the gear at prescribed speeds and locations of the machine such as loading, heating, marquenching/rolling, and unloading positions, as shown in figure 5. Total linear travel will depend of the machine design but should be kept to a minimum in order to minimize part transfer times. Position control of the linear axis is required in order to position the part in the various positions required for processing.

#### *c. Control Functions Required for the Induction Heating Process & Machine*

The induction heating equipment will be fully integrated with the other machine subsystems both mechanically and with the process and machine controller. The induction heating equipment may be treated as an independent subsystem, and the controller will switch the MF and RF induction power supplies on and/or off at the appropriate times, and at the set power levels, based on selected recipe for any candidate gear. Additionally, the controller will operate the induction scanner servo-drives for gear rotation and the axial movement of the gear, again based on the machine settings established for a candidate gear.

### *3. Ausforming Oil Heating/Recirculating System*

The oil heating subsystem will be a stand-alone type equipment requiring on/off and set point specifications. The oil heating system is required to:

(a) Preheat the oil in the storage tanks,
(b) pump the oil into the main processing tank,
(c) heating and circulation of oil in the main processing tanks,
(d) pumping out of the oil from the processing tank to the storage tanks.

The processing and storage tanks must have oil level monitors as well as sensors to detect any catastrophic failures and the system interlinked for emergency E-stops. Integral with the system is the means to filter the oil (40 μm) and a debris monitoring system to provide oil change requests when one is required.

The environment control system provides an inert gas atmosphere in the enclosed chamber to protect the workpiece gear from surface oxidation during the induction heating cycle and to minimize degradation of the heated processing media. The environment control system includes an air cleaning unit, an oxygen analyzer, ducting and control valves and vents to purge the enclosed chambers with air or inert gas. Interlocking gates and sensors are to be provided to ensure safe operation of the system.

### *4. Gear Loading/Unloading System*

An automated load/unload system will be included in the machine as manual operation in the close vicinity of hot oil is not desirable. A pick and place mechanism is envisioned as the device for the load and/or unload operations. Two possible versions are proposed.

a. This alternative mimics the scanner locations, as shown in figure 5. The scanner with the gear, retracts to the load position after all processing is complete, for the unload operation. A common, pick and place mechanism conducts the load and unload operation which is integrated to the means that brings a preausform finished gear to the machine and takes away the finished gear from the machine.

b. In option a, the machine idles while the gear is being unloaded. In order to eliminate this idling, the gear can be released from the scanner spindle at the bottom end of its stroke, after the roll finishing operation is complete, on to an inclined conveyor that carries the gear out of the oil tank and out of the machine. The scanner spindle retracts and is immediately available for gear loading.

Other options may also be considered that minimize machine idle time.

## 5. *Ausforming Process and Machine Controller*

The process and machine controller will interface with the gear roll finishing machine, the induction heating system (including the power supplies and the induction scanner), and the ancillary equipment. The direct realtime control actions for the controller include (a) infeeding and servo-drive to the dies for the roll finishing step, and (b) linear and rotational motion of the gear during the induction heating step. The indirect realtime control actions of the controller include the loading and unloading of the gear, induction power level and duration controls, and other support functions. It appears that all control requirements, other than the servo-controlled drives and the EGB, should be handled by a standard, commercial programmable logic controller (PLC). Figure 7 shows a schematic of the control architecture that will be required for analog interface and associated signal conditioning hardware, serial interface for intelligent servo-drive including the sensing capability, and digital interface for the various machine subsystems.

The induction scanner axis and the dies infeed axis constitute the two linear axes that need to be controlled. The positioning accuracy of the scanner axes should be ±0.001", while that required for the infeed axis is ±0.0005".

It is preferred that the machine controller synchronize the two rolling dies through an EBG with a 1:1 ratio. Furthermore, the servo-drive motor providing rotation of the gear on the scanner axis may also be equipped with additional instrumentation to sense and orient the gear for rotational phasing with the dies, thus providing a sophisticated gear meshing capability

The control software will be structured in a manner that allows for activation and actuation of the various sub-systems of the machine in a manual and sequential manner, to ensure the proper functioning of the system. It should then be possible for the control system to be set into a fully automatic mode for the continuous processing of parts as they are presented to the loading mechanism. Sufficient sensing and monitoring of all parameters will be necessary to detect any inappropriate event and stop the process or take remedial action, if possible. Standard safeguards to ensure safe operation will also be provided.

Table 1: Summary of Machine Specifications

| | | |
|---|---|---|
| **1.** | **Range of gear dimensions** | |
| | a. Outer Diameter | 1 to 2" |
| | b. Face width | 2" max |
| | c. Tooth thickness tolerance | ± 0.001" |
| | d. Bore tolerance | ± 0.001" |
| | e. Overall gear dimensions | ± 0.002" |
| | f. Gear types and shapes | With bore, on integral shafts, multiple gears on a shaft |
| **2.** | **Infeed of Rolling Dies** | |
| | a. Infeed load | 40,000 lbs max |
| | b. Amount of deformation | 0.003" per flank max |
| | c. Infeed stroke | 1" max (for a specific diameter gear) |
| | d. Infeed positional accuracy | ±0.0005" |
| | e. Infeed profile | Linear from tight mesh to final infeed |
| | f. Infeed motion needed | From outside of gear to mesh - to tight mesh - and then to full load infeed (final) |
| | g. Infeed from tight to final position | 0.010" max |
| | h. Die diameter | 10" max |
| | i. Die face width | Gear face width + 0.5" max |
| | j. Die axis adjustments | Needed as machine set up<br>In plane<br>Out of plane<br>Axial |
| | k. Hardware/procedures | Needed to mesh dies with gear |
| **3.** | **Servo-Drive to dies** | |
| | a. HP | 25 hp max |
| | b. Die rotation | 60 to 180 rpm variable |
| | c. Drive to dies | Synchronous drive to both dies, EGB or Mechanical |
| **4.** | **Induction heating (MF and/or RF as required by component design)** | |
| | a. MF Power | 150 kw max |
| | b. MF Frequency | 2.8 - 10 kHz |
| | c. RF Power | 150 kw max |
| | d. RF Frequency | 250 - 400 kHz |
| | e. Rotational speed | 800 rpm max, variable |
| **5.** | **Critical Gear Transfer Times** | |
| | a. Gear load position to MF heat coil | Not critical |
| | b. MF heat time | 6 sec max |
| | c. Transfer from MF to RF coil | 0.2 sec max |
| | d. RF heat time | 1.0 sec max |
| | e. Transfer from RF to inside oil | 0.25 sec max |

| | | |
|---|---|---|
| f. | Marquench/roll finish time | 10 sec max |
| g. | Unload | Not critical |

**6. Ausform Processing Media Details**

| | | |
|---|---|---|
| a. | Max oil temperature | 475°F |
| b. | Processing Media | Houghton Martemp-2525 oil or other if acceptable |
| c. | Marquench/roll finishing duration | 10 seconds max |
| d. | Oil clean/filter | Yes (40 µm) |
| e. | Oil heat and recirculating | Yes, in processing and storage tanks |
| f. | Temperature regulation | ± 2°F |

Figures:

Figure 1 Ausforming Process Schematic

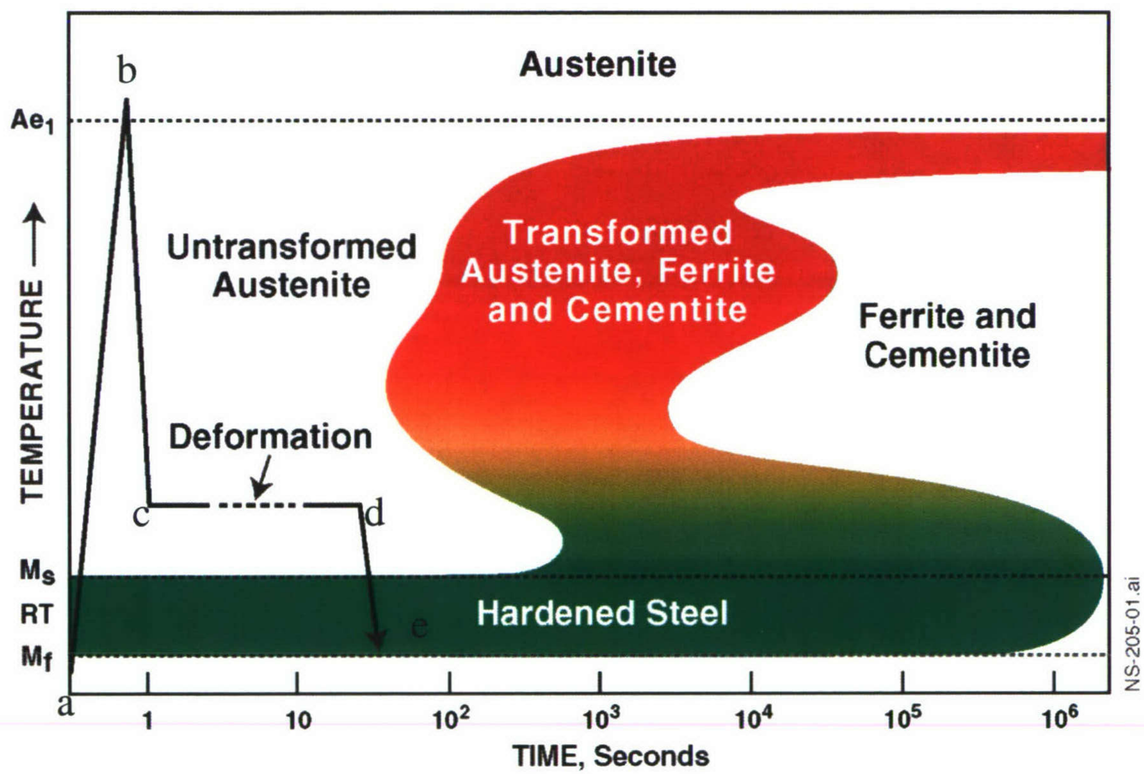


Figure 2 Double die ausform gear finishing schematic

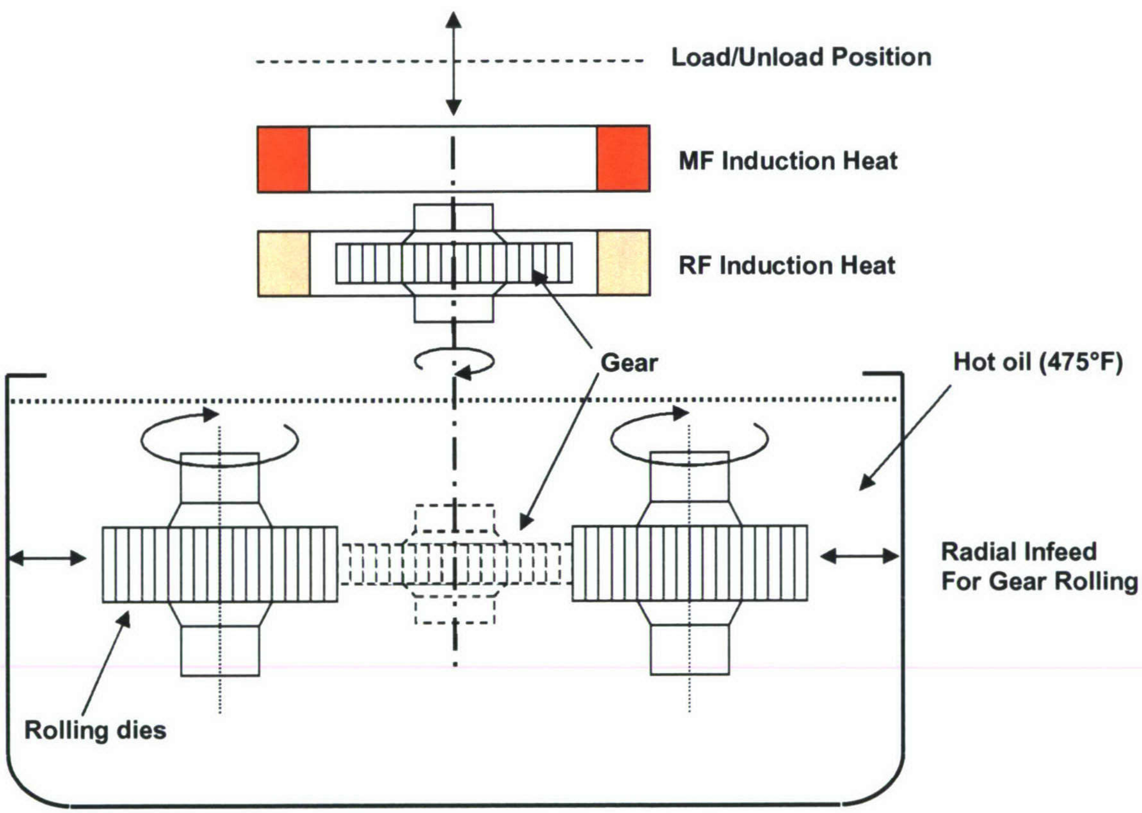


Figure 3 Double die gear roll finishing machine schematic

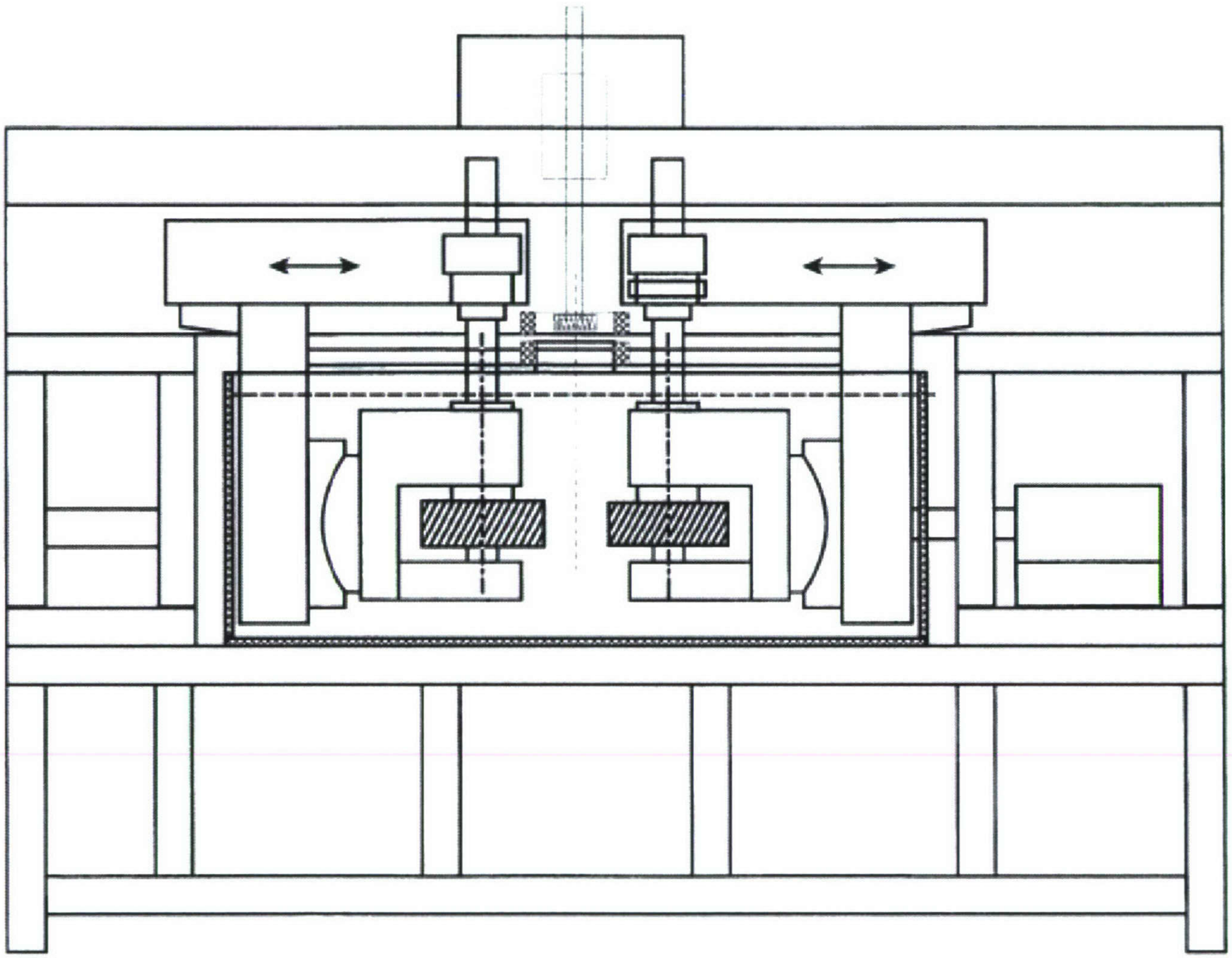


Figure 4 Side view schematic of the machine

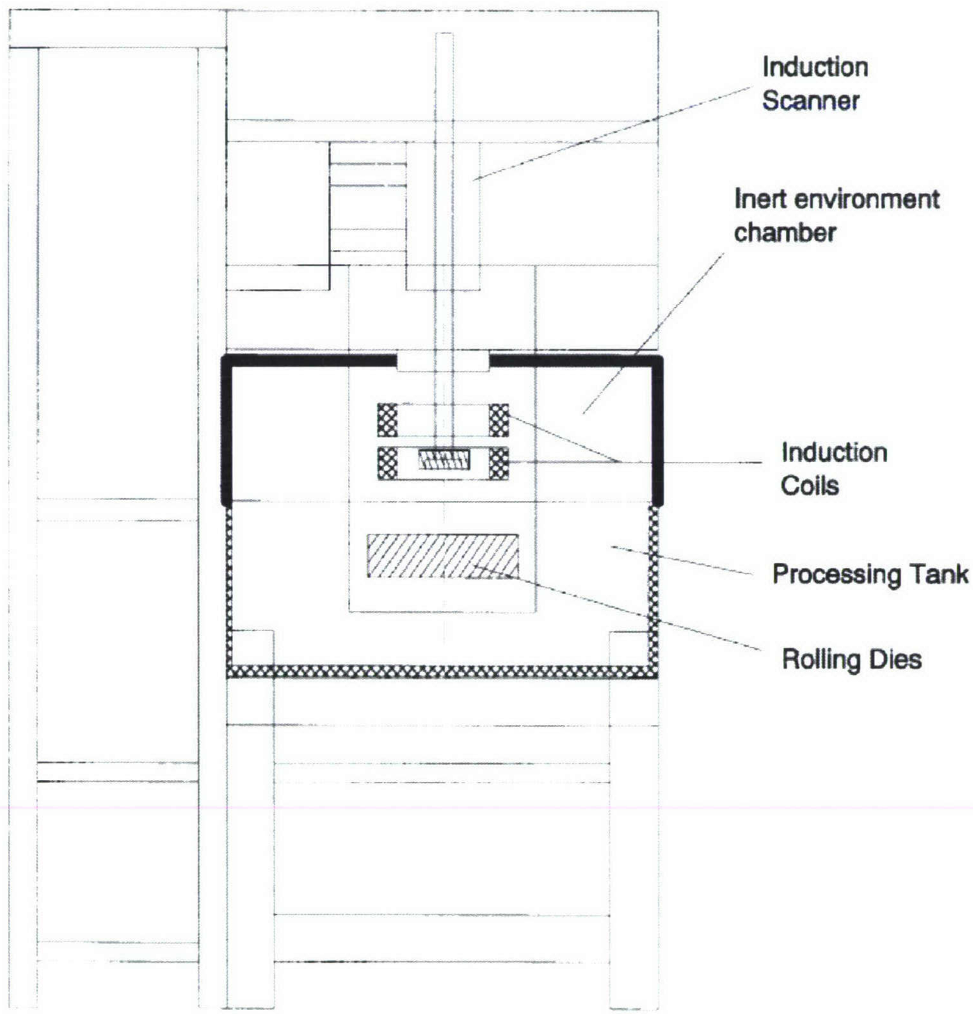


Figure 5 Schematic description of induction scanner

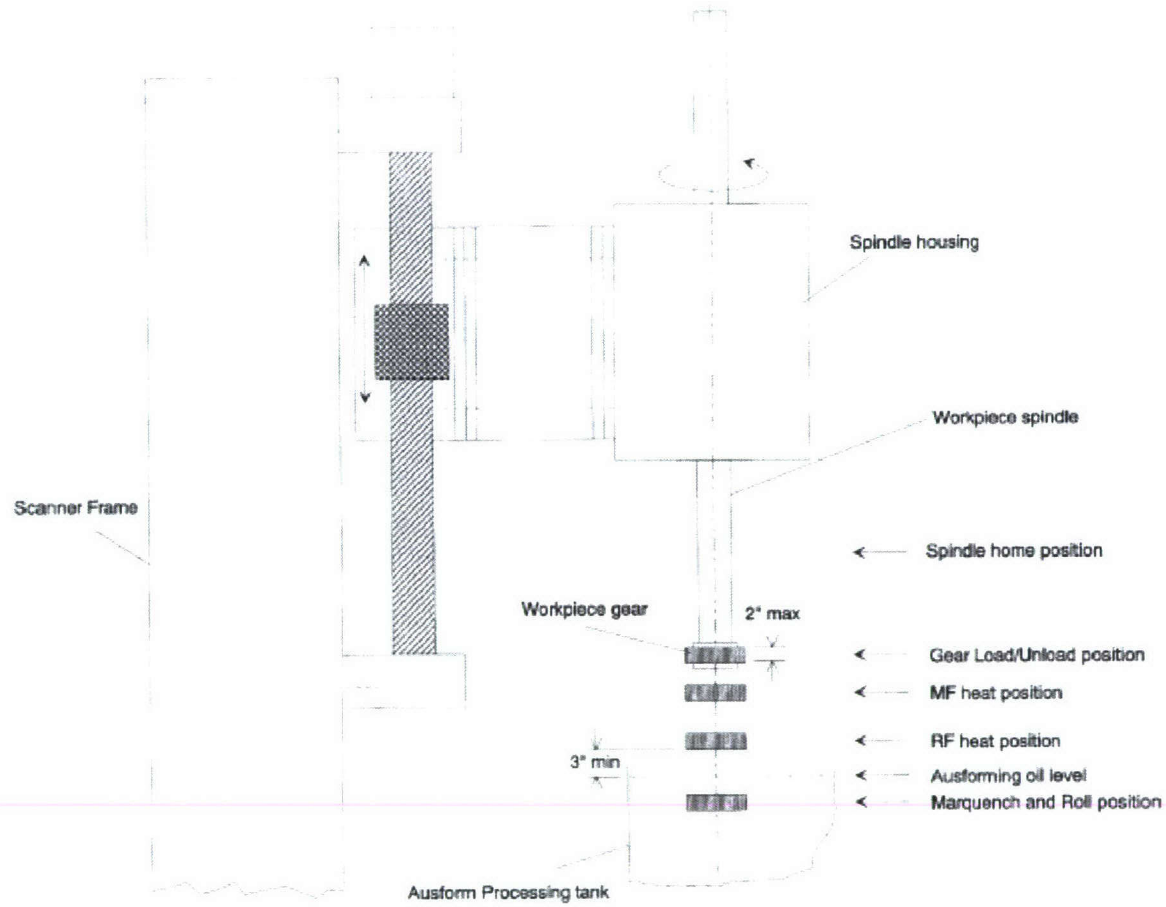


Figure 6 Schematic oil heating system

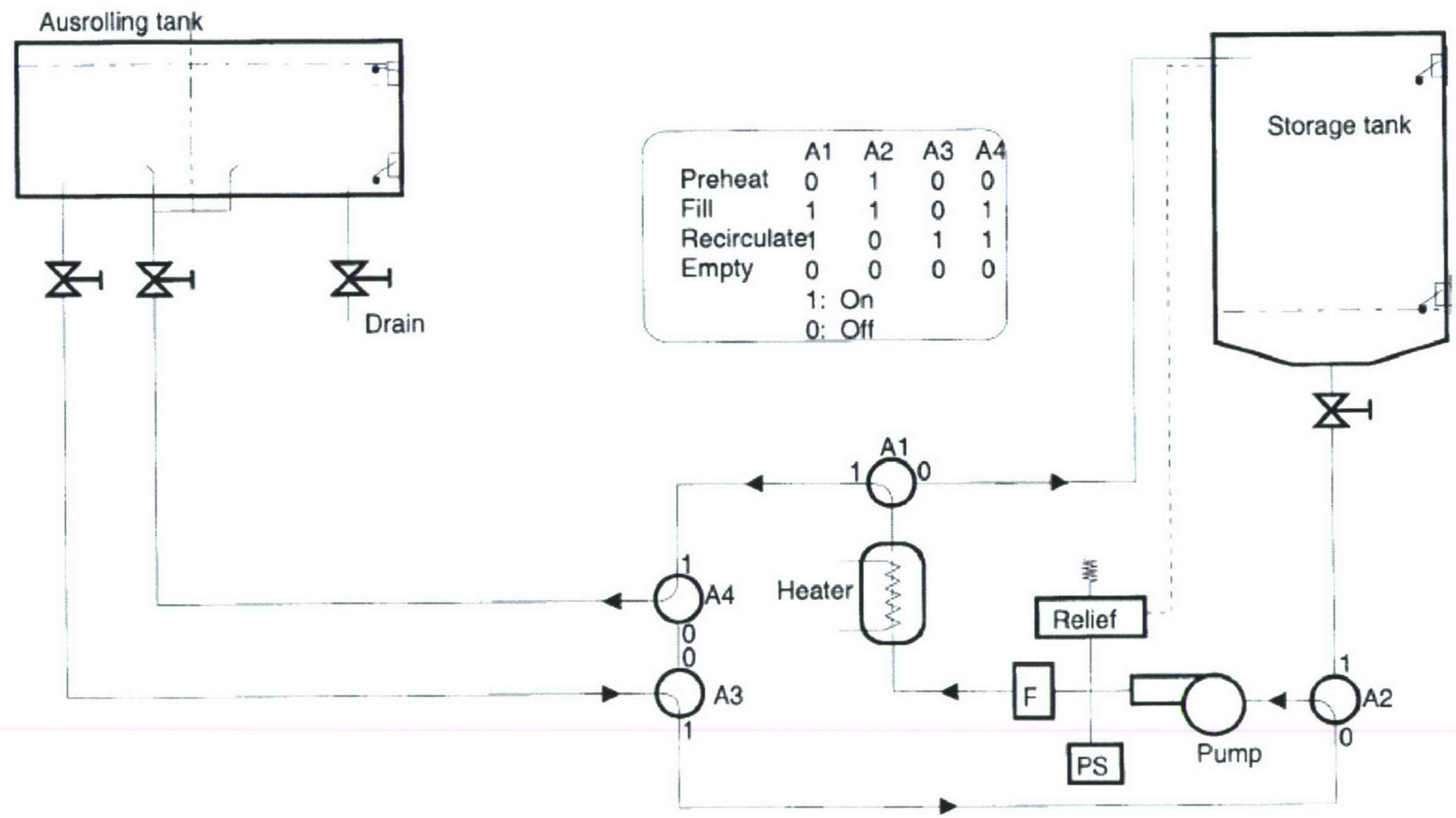
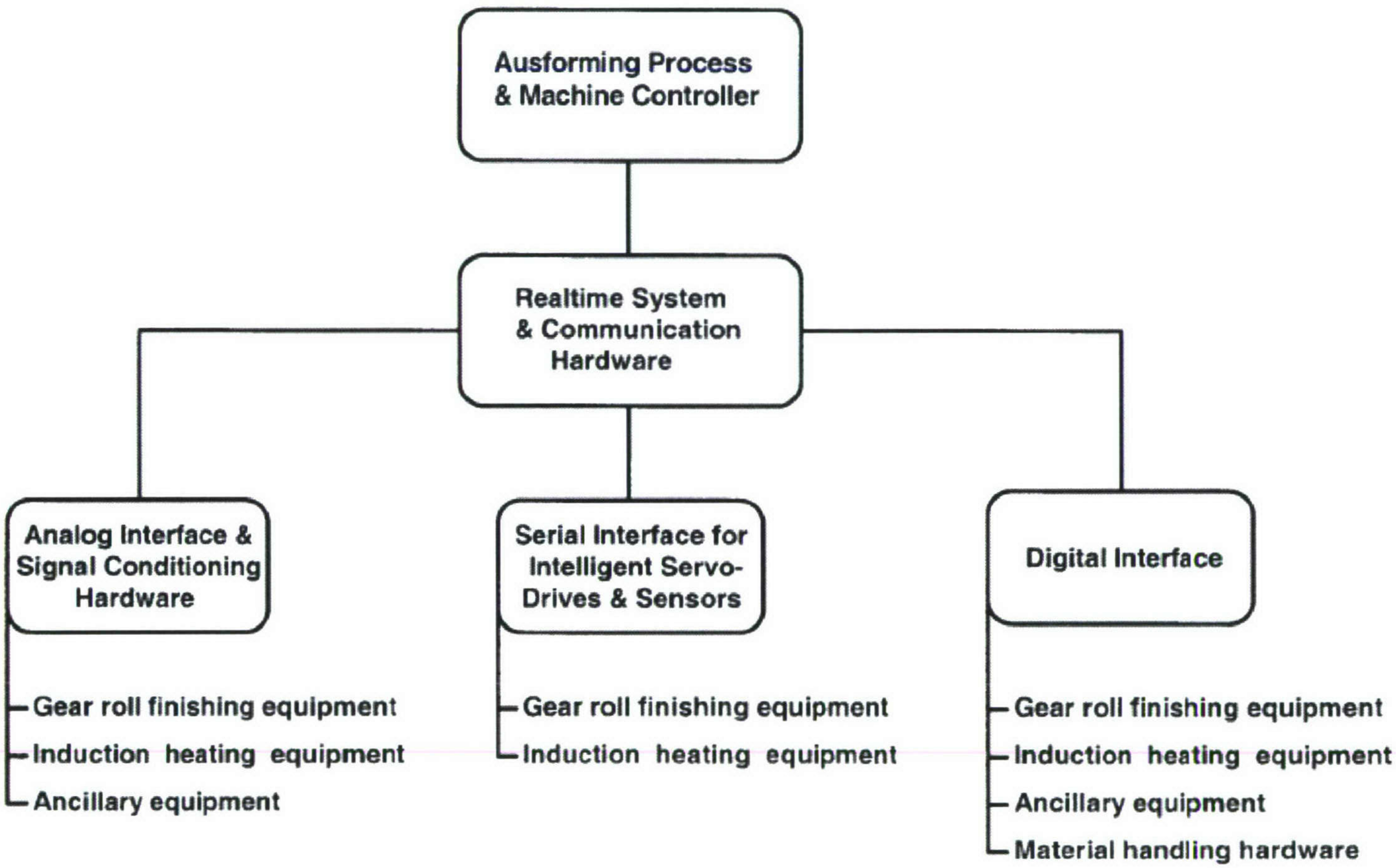


Figure 7 Ausforming process and machine control architecture



**Appendix B**
**High Strength P/M Gears for Vehicle Transmissions-Phase II**
**Contract No. N00024-02-D-6604, Task Order 0317**
**T.D. #4101093**

Preliminary Design Report
(ARL/Penn State Project No. 13964)
By
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Submitted to
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Background: Based on the successful completion of the phase I effort, the phase II effort involves developing the design package to define the production P/M gear ausform finishing machine. To get intimate industry involvement in this project so as to enable a seamless transition to the manufacturing sector and benefit the sponsor (US Army), it was decided to work with machine tool builders in several stages. The concept design package developed as "Production Gear Ausform Finishing Machine-Concept Design" was shared with three prominent US based machine tool builders, Kinefac Corporation of Worcester Massachusetts, Normac Inc. of Arden, North Carolina and Gleason Corporation of Rochester, New York. Two organizations, Kinefac and Normac expressed interest in further exploring this opportunity to design and build the production machine.

Based on several visits by both organizations to Penn State and Keystone P/M company, two preliminary design packages were submitted along with cost proposals to design and build their respective designs. A final PDR meeting was held on 24 August, 2007 to review the two preliminary design packages and determine which was considered the preferable option to pursue for detail design and build (attendees were Dr. David Alven and Mr. Gary Anderson from Keystone P/M Company, Mr. Rick Weyer from Penn State IP Office and Drs. Nagesh Sonti and Suren Rao from ARL/Penn State). This report summarizes the design developed and the rationale for the down-select.

Kinefac Preliminary Design: Kinefac Corporation is an established manufacturer of thread rolling equipment, among other metal forming equipment. The Kinefac approach is based on modifying a current machine thread rolling machine design to incorporate all the necessary characteristics of P/M gear ausform finishing. Figures 1 a, b and c describe the preliminary Kinefac design package.

Normac Preliminary Design: Normac, Inc., is a manufacturer of light grinding equipment, normally associated with tool grinding. Consequently, their concept and preliminary design is based on starting with a "clean sheet" of paper. They appeared to have considerable difficulty with the concept design data provided them, which specified the high rolling loads encountered in ausform finishing, possibly because of lack of experience in metal forming. Their preliminary design is illustrated in figure 2.

Preliminary Design Review: Kinefac's experience in metal forming and more specifically thread rolling clearly demonstrated a superior preliminary design. The review meeting was then focused on the deficiencies of the Normac design and some of these items are listed below.

1. The Normac preliminary design package was not detailed enough in comparison to the Kinefac design package.
2. Normac' in-feed axis was a part-dependent, self-centering system which was less desirable than the Kinefac machine centered system.
3. The primary infeed actuator was unspecified by Normac, as both a hydraulic and ball screw type actuators were under consideration. The Normac preferable actuator was a ball screw based system, which would be difficult to design for the anticipated rolling loads of 40,000 pounds force.
4. The Normac design did not utilize a tailstock support for the workpiece, unlike the Kinefac design, which was unacceptable.
5. There were automated, work loading/unloading concerns with the Normac design because of the location of the infeed mechanism actuator.

It was obvious that Kinefac's experience in rolling processes influenced their design, while Normac's lack of experience was evident in theirs. There was unanimous consensus that the Kinefac design was the lower risk option and would be the technically feasible option to pursue to the detail design and build phase.

The two interested machine tool builders had also submitted detail design and machine build costs. Keystone had requested that these costs be submitted without including control system design and implementation costs. Since the actual procurement of the hardware would utilize funds other than Federal project funds, Keystone planned to design, procure and integrate the control system (hardware and software) to the machine tool utilizing internal resources. This would minimize Keystone's "out of pocket" expenses. While Kinefac was responsive to this request and submitted a cost proposal without inclusion of the control system. Normac, however, did not feel this was appropriate and submitted a cost proposal that included design and implementing of the control system, while agreeing to absorb control system design costs. Because of this difference between the two proposals a direct cost comparison is not possible but enough cost break down was provided to conduct the cost comparison provided in table 1.

Conclusion: The technical review identifies the Kinefac preliminary design as the preferable option. This in conjunction with cost proposal identifies the Kinefac preliminary design as the desirable option to pursue.

A visit to verify the institutional integrity of Kinefac Corporation followed this preliminary decision. A review of their organization, key personnel and facilities during the visit on 31 August, 2007, reinforced the validity of the decision. The detail design aspect of the machine will be initiated shortly.

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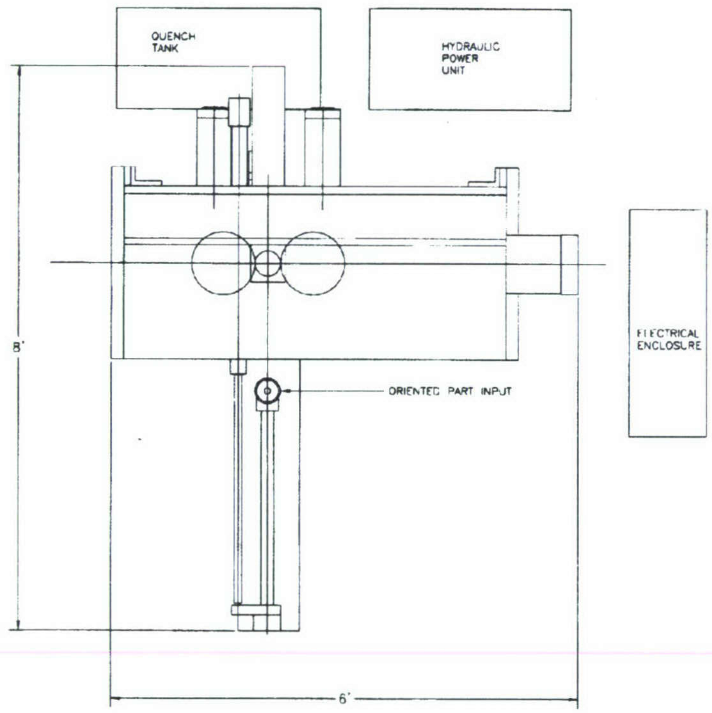


Figure 1A Kinefac Preliminary Design

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DO NOT SCALE DRAWING

KINEFAC CORPORATION
WORCESTER, MASS.

SCALE 1/8 | DRAWN BY CJC
DATE 05/15/2007 | DESIGNED BY HAC

TITLE MC-20 FI CNC (V) - AUSFORM KINE-ROLLER SYSTEM

DRAWING NUMBER 174140 1 OF 3

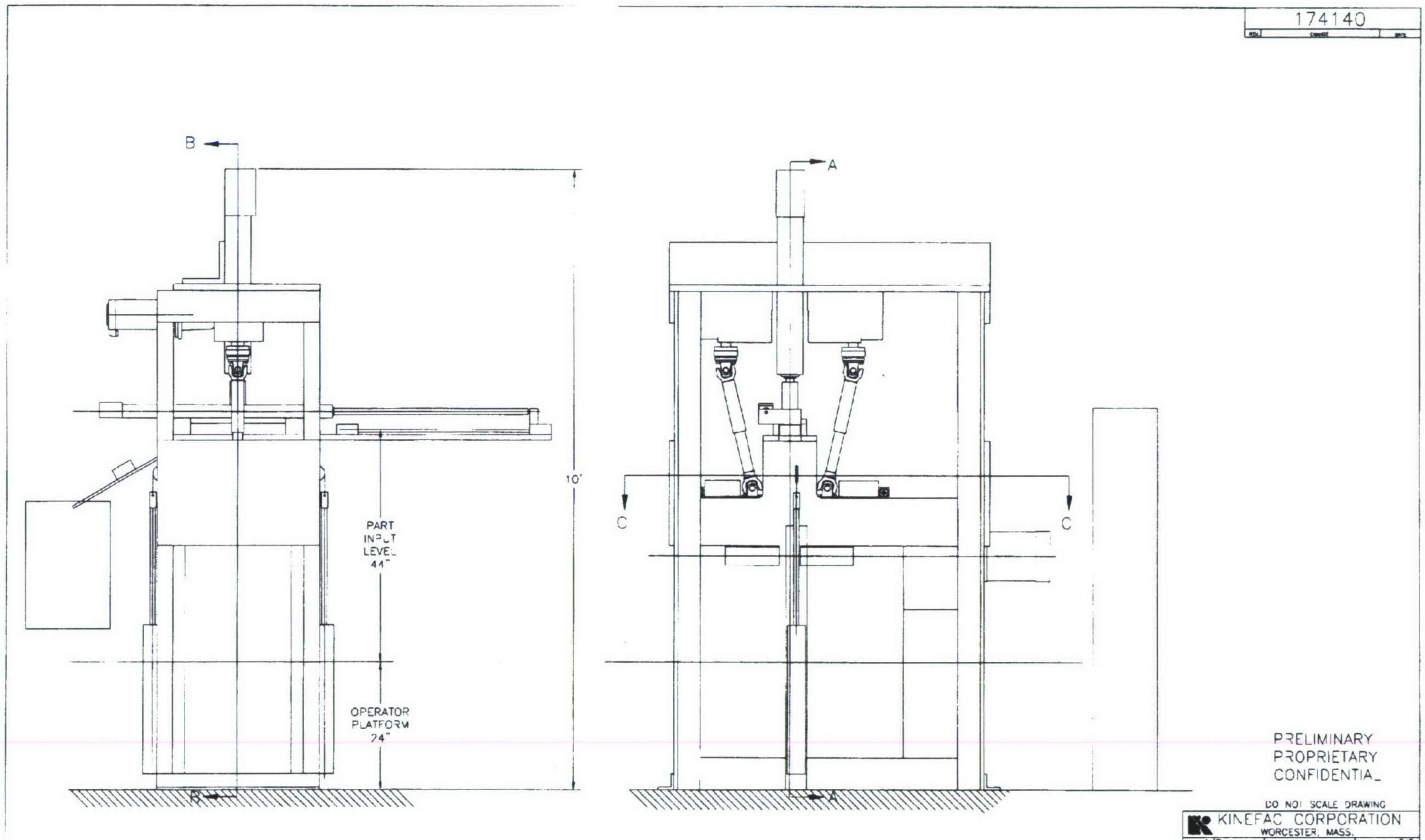


Figure 1B. Kinefac Preliminary Design

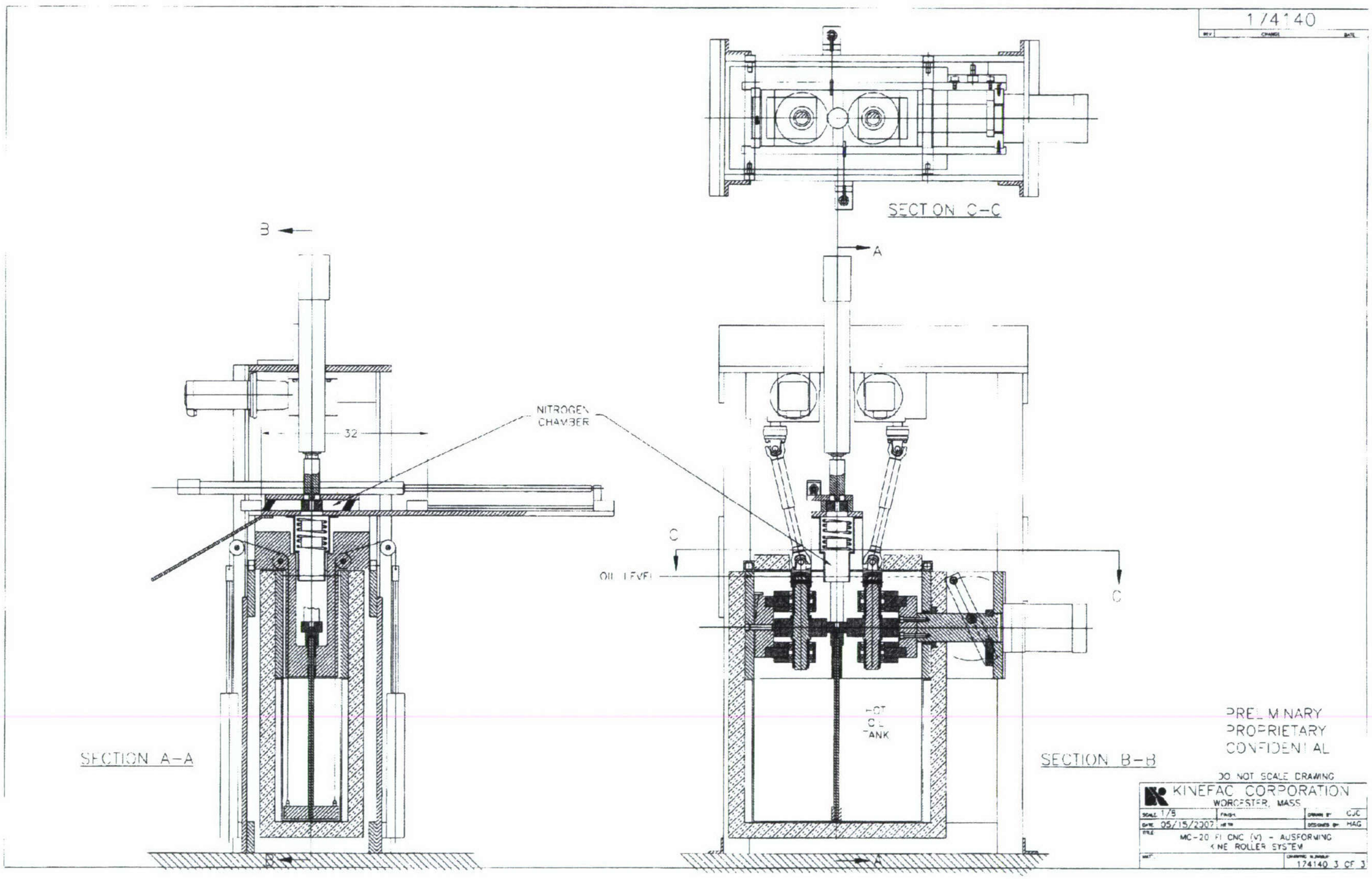


Figure 1C. Kinefac Preliminary Design

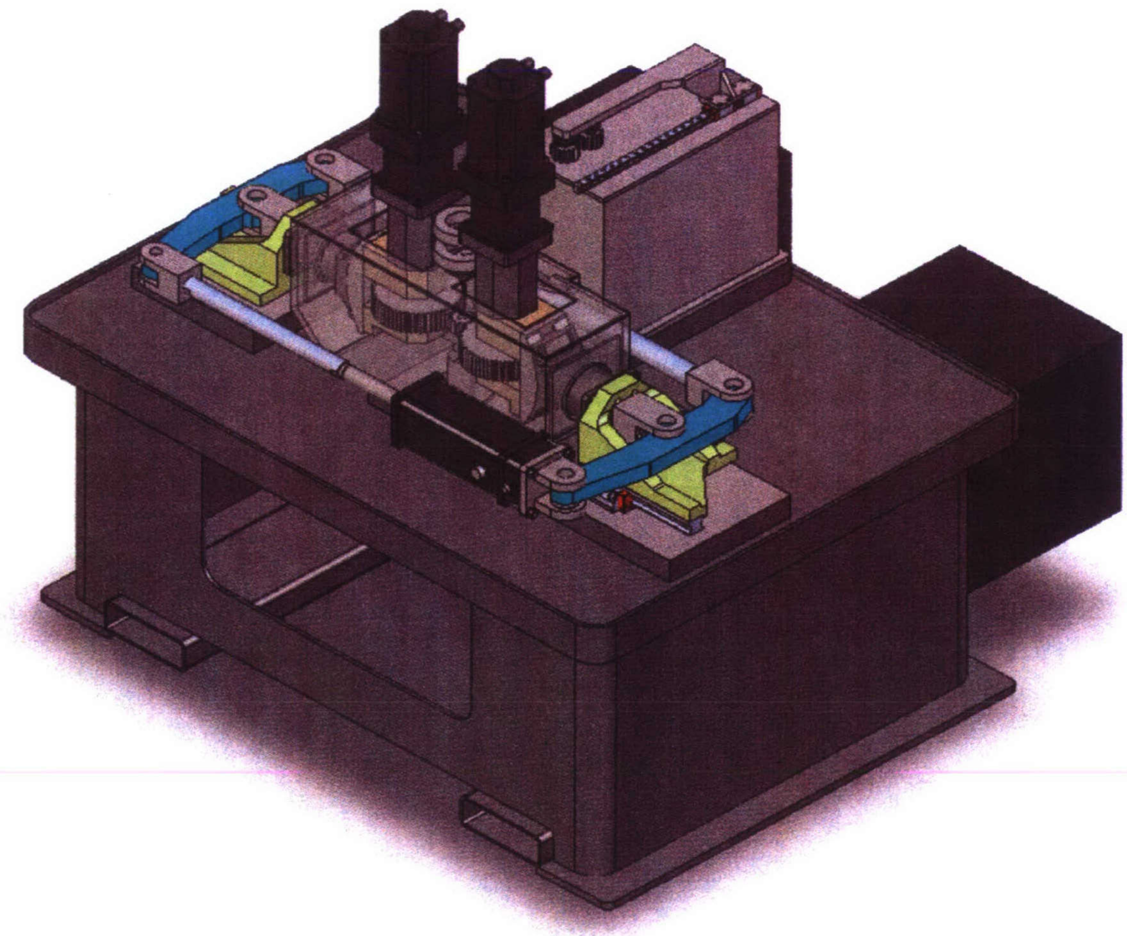

Figure 2. Normac Preliminary Design

# P/M Ausform Finishing Machine Proposals

**Table 1: COST COMPARISON**

| Vendor | Eng. w controls | Eng. wo controls | Build w controls | Build wo controls |
|---|---|---|---|---|
| Kinefac | | $181,000 | | $194,000 |
| Normac | $200,000 | $200,000 | $390,000 | $310,000 |

## Appendix C

Machine and Integration; Mechanical, Electrical and Control System
Assemblies, schematics and all details

**Distribution to Sponsor Only**

**Bound book separate from report**